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Pull and Creep Tests on Gypsum-Bonded Roof Bolts

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Donald Paul Hodel, Secretary

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT			
cm^3	cubic centimeter	lb	pound
°C	degree Celsius	lb/min	pound per minute
d	day	min	minute
ft	foot	mm	millimeter
g	gram	µm	micrometer
h	hour	pct	percent
in	inch	r/min	revolution per minute
in/ft	inch per foot	s	second
in/h	inch per hour	vol pct	volume percent
L	liter	yr	year

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PULL AND CREEP TESTS ON GYPSUM-BONDED ROOF BOLTS

By J. S. Hansen[1] and S. J. Gerdemann[2]

ABSTRACT

To improve mine safety, the Bureau of Mines has conducted a search for better materials and systems to anchor roof bolts. This report describes a study on the ability of a gypsum-based anchoring medium to withstand short- and long-term loads.

Results showed that 2-ft-long bolts anchored with gypsum that was injected as plaster slurry at a 0.370 water-cement ratio and cured for 10 min sustained pull test loads equal to the ultimate strength of the bolt steel (about 37,000 lb). For comparison, the minimum required capacity is 17,600 lb. Long-term loads of 15,500 lb were sustained with estimated 10-yr movement of less than 1/2 in.

Two-foot-long bolts anchored with gypsum installed in a cartridge in which the water was contained in tiny capsules sustained a pull test load of about 30,300 lb at a 0.319 water-cement ratio and 10-min cure time. At a 0.288 water-cement ratio, load capacity was about 37,000 lb. The lower load capacities of cartridge-installed bolts resulted primarily from the remnants of the water-wax capsules. Above 10,000 lb, creep movement of cartridge-grouted bolts appears excessive, but longer bolts may be capable of resisting creep better.

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INTRODUCTION

It is established practice to use roof bolts to support roofs and ribs in coal, metal, and nonmetal mines. The most commonly used bolt is mechanically anchored at the end opposite the bolthead by a device that contacts the hole wall when the bolt is tensioned. Through tensioning, the layers of rock between the bolthead and anchor are tied together to form a "beam" that supports itself as well as the rock above it.

In 1970, an innovative bolting system was introduced that relied upon polyester resin to bond the bolt to the rock along its entire length.[3] Among its advantages, the fully anchored bolt provided excellent resistance to roof shear and to high, induced tension in the presence of roof parting. Although by no means dominating the market, it was estimated that more than 20 million full-column bolts would be installed in 1980.[4] Cost has been the major drawback to more widespread use of resin-grouted bolts.

In accord with Bureau goals to improve the safety of mines and mining, the Bureau of Mines conducted a search for new, lower cost bonding materials to substitute for polyester resins as an anchoring medium.[5] Because high early strength was also a criterion, many common cementitious materials, such as portland and aluminate cements, were rejected early in the search. The cement showing the most promise was composed of calcium sulfate hemihydrate ($CaSO_4 \cdot 1/2H_2O$, plaster of paris) and a small amount of potassium sulfate (K_2SO_4) accelerator, which together form primarily gypsum upon hydration. Apparently meeting all criteria, the accelerated gypsum was low in cost, nontoxic, and fast setting, and developed more than adequate strength in less than 5 min.

Two systems were devised for installing roof bolts with the new cement. In one, water and accelerated hemihydrate are injected simultaneously into a roof-bolt hole, and a roof bolt is installed. Within 10 to 20 s, the hardening reaction begins to set the bolt. In the second system, referred to as the cartridge system,[6] the accelerated hemihydrate is blended with water capsules and placed into a long plastic wrapper. The water capsules consist of less than a drop (0.05 cm^3) of water that is surrounded by a thin wax shell. The cartridge is inserted into a hole, the bolt is installed, and the wrapper and water capsules rupture, initiating the hydration reaction and hardening.

This study was undertaken at the Bureau's Albany (OR) Research Center to determine the load capacity of bolts installed with each system under both normal and limiting conditions and to determine the amount of bolt movement that could be expected over extended time periods under various loads. The criterion for load capacity has been set at 17,700 lb for a 3/4-in-diam, 30-in-long bolt within 10 min after installation.[7] This figure is derived directly from the minimum yield strength requirement for ASTM

[3]Gerdeen, J. C., V. W. Snyder, G. L. Viegilahn, and J. Parker. Design Criteria for Roof Bolting Plans Using Fully Resin-Grouted Nontensioned Bolts To Reinforce Bedded Mine Roof. Volume I. Executive Summary and Literature Review (contract J0366004, MI Technol. Univ.). BuMines OFR 46(1)-80, 1977, 208 pp.; NTIS PB 80-180052.

[4]Simpson, R. E., J. E. Fraley, and D. J. Cox. Inorganic Cement for Mine Roof-Bolt Grouting. BuMines RI 8494, 1980, 32 pp.

[5]Work cited in footnote 4.

[6]Simpson, R. E. Cartridge for Grouting an Anchor Element in a Hole of a Support Structure. U.S. Pat. 4,096,944, June 27, 1978.

[7]Work cited in footnote 4.

A-615 grade 40 rebar[8] of which most bolts are made. In this report, the 17,700-lb criterion is used for comparison of all load capacities. Since no limit has been established, roof movement of up to 1 in was deemed acceptable and is also used for comparison.

MATERIAL PROPERTIES

COMPOSITIONAL AND STRUCTURAL PROPERTIES OF BONDING MATERIAL

The primary raw material for making anchoring cements (commonly called grout) was purchased in large lots. While one brand was arbitrarily chosen, samples from several brands were subjected to chemical, X-ray, and scanning electron microscopic (SEM) analysis. A surprising uniformity was found. The material consisted of 99+ pct calcium sulfate hemihydrate ($CaSO_4 \cdot 1/2H_2O$) with minor traces of aluminum, magnesium, silicon, and titanium. (Generically, and in this report, the hemihydrate state is referred to as plaster of paris, and the hardened calcium sulfate dihydrate product that forms upon mixing with water is referred to as gypsum.) With the exception of one brand that was light grey, most brands appeared bright white. The grey-colored brand contained slightly higher levels of aluminum and silicon and, in addition, iron. The trace elements probably existed as impurities since such low levels would not be added for effect.

The plaster hydration level was determined by loss on ignition (LOI) and X-ray analyses. The average LOI at 600° C was 6.3 pct. In comparison, the theoretical hydration of plaster is 6.2 pct, indicating that a small portion of the samples was calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$). X-ray diffraction analysis confirmed the existence of dihydrate at levels of 1 to 2 pct.

Normally, hydrated plasters solidify over an extended time period up to an hour, depending upon such factors as fineness, degree of mixing, and water-cement ratio. However, because the demands of roof bolting require that solidification be considerably shorter, a small amount of potassium sulfate (K_2SO_4) was blended with all plasters to reduce the set time. (With accelerator, solidification begins within 15 s after hydration, the grout is completely solid within 1 min, and significant strength is obtained within 3 min.) Powdered reagent-grade accelerators were used, and the water for hydration was distilled.

MICROPROBE AND SEM OBSERVATIONS OF PLASTERS AND GYPSUMS

Plaster samples were similar and consisted of small particles that were 10 µm or less in length, interspersed with less numerous, larger particles that were 50 to 100 µm in length. The particles were generally one-fifth as wide as long, and each had a layered, platelike appearance with sharp, stepped edges along the lengthwise direction. Figure 1 is an SEM micrograph of plaster that is typical of several lots and several brands.

To determine the morphology of gypsum, cast samples were made from plasters that were mixed for 10 s with distilled water at a water-cement ratio of 0.300. (In mixing portland and other cements, the water-cement ratio is the ratio of the weight of the mixing water to the weight of cement. In this context, cement is synonymous with plaster.) SEM micrographs of the top, undisturbed sample

[8]American Society for Testing and Materials. Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement. A 615-76a in 1976 Book of ASTM Standards: Part 4, Structural Steel; Concrete Reinforcing Steel; Pressure Vessel Plate and Forgings; Steel Rails, Wheels, and Ties; Steel Fasteners. Philadelphia, PA, 1977, pp. 570-575.

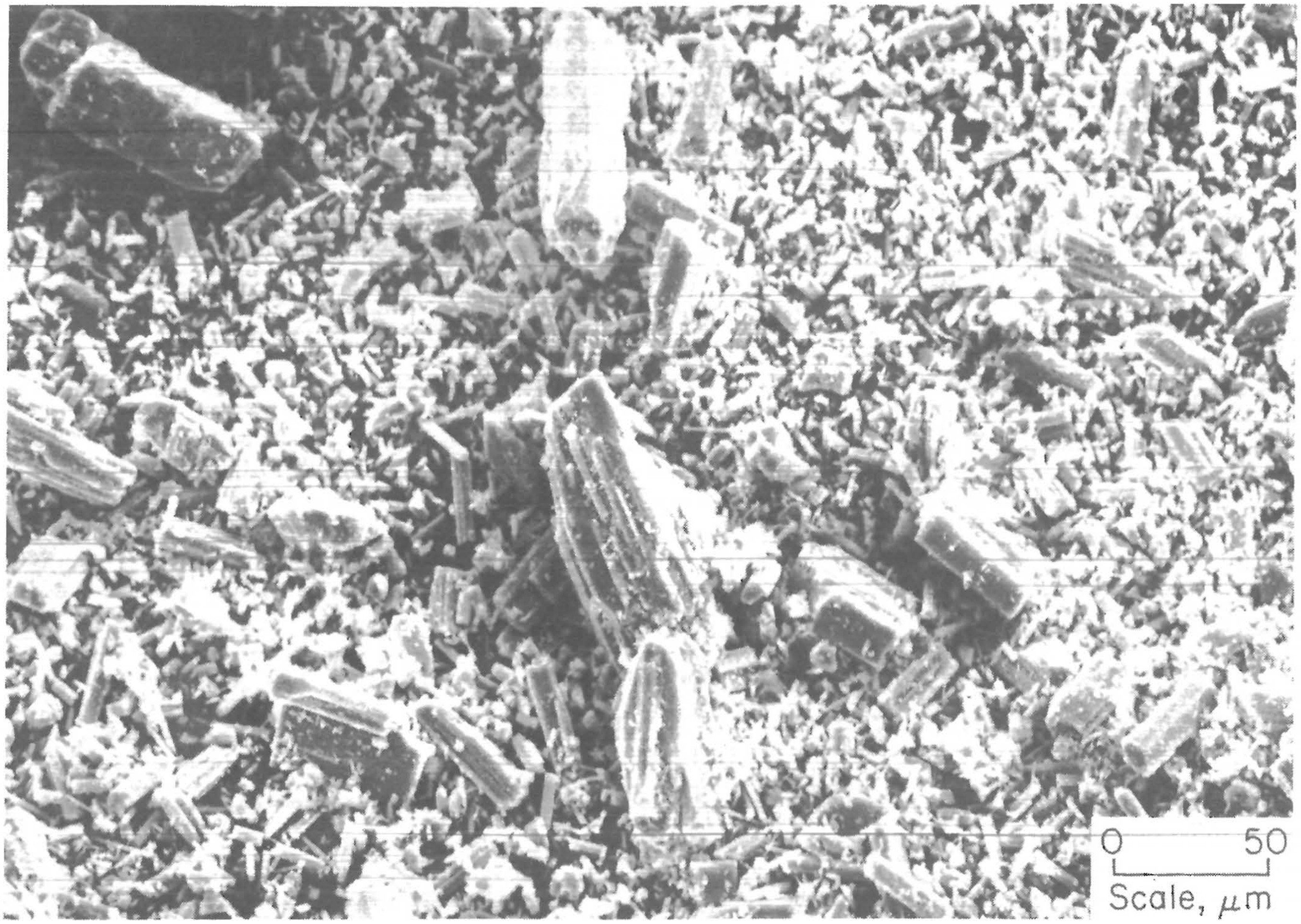

FIGURE 1. - SEM micrograph of typical plaster used to make inorganic grout.

surfaces revealed no discernible sample-to-sample differences. The gypsum crystallites, shown in figure 2, were flat, layered, 10 µm or more long, and fused.

Additional samples were cast with 1.5 pct accelerator and the same water-cement ratio, and also without accelerator and a 0.400 water-cement ratio. The gypsum crystallites of the accelerated sample, shown in figure 3, were shorter, less layered, and more cylindrical than the unaccelerated samples. Presumably, the accelerator provided many sites for gypsum formation from the plaster, which in turn inhibited crystal growth. Although the accelerator was not separately identified in the SEM micrographs, microprobe photographs of potassium-specific traces, figure 4, showed that the accelerator was not evenly distributed. However, adverse effects rising from the uneven distribution were not noted.

Figure 5 shows that the morphology of the sample cast at the 0.400 water-cement ratio was similar, but that the gypsum crystallites were approximately twice as long. Recrystallization most likely occurred at a slower rate, leaving the crystallites extended time to grow. The excess water decreased the mix density and created more and larger pores upon drying. Larger and more numerous pores, of course, result in weaker structures.

CARTRIDGE MAKEUP

Cartridges were made by combining accelerated plaster with microcapsules of water that measured 1 to 2 mm in diameter. The microcapsules were commercially

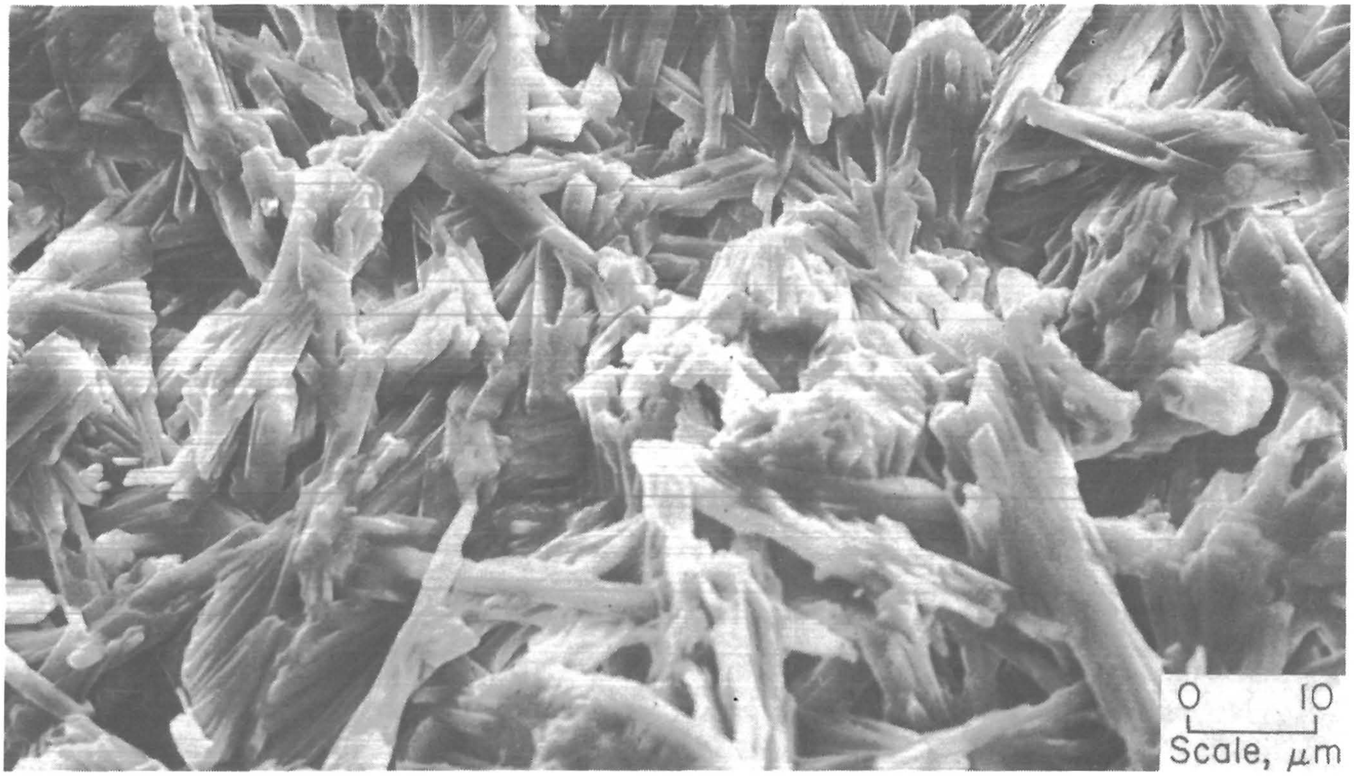

FIGURE 2. - SEM micrograph of undisturbed surface of gypsum cast at a 0.300 water-cement ratio and no accelerator.

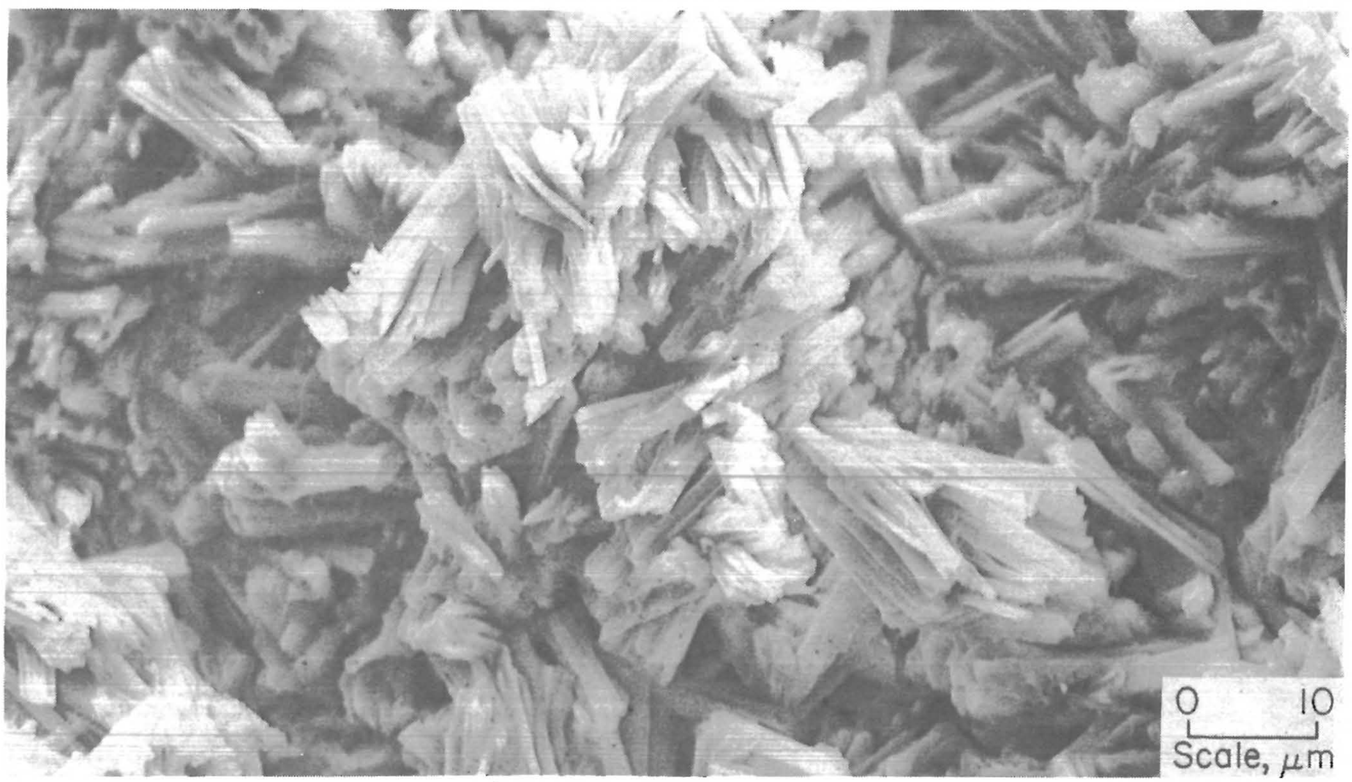

FIGURE 3. - SEM micrograph of undisturbed surface of gypsum cast at a 0.300 water-cement ratio and 1.5 pct accelerator.

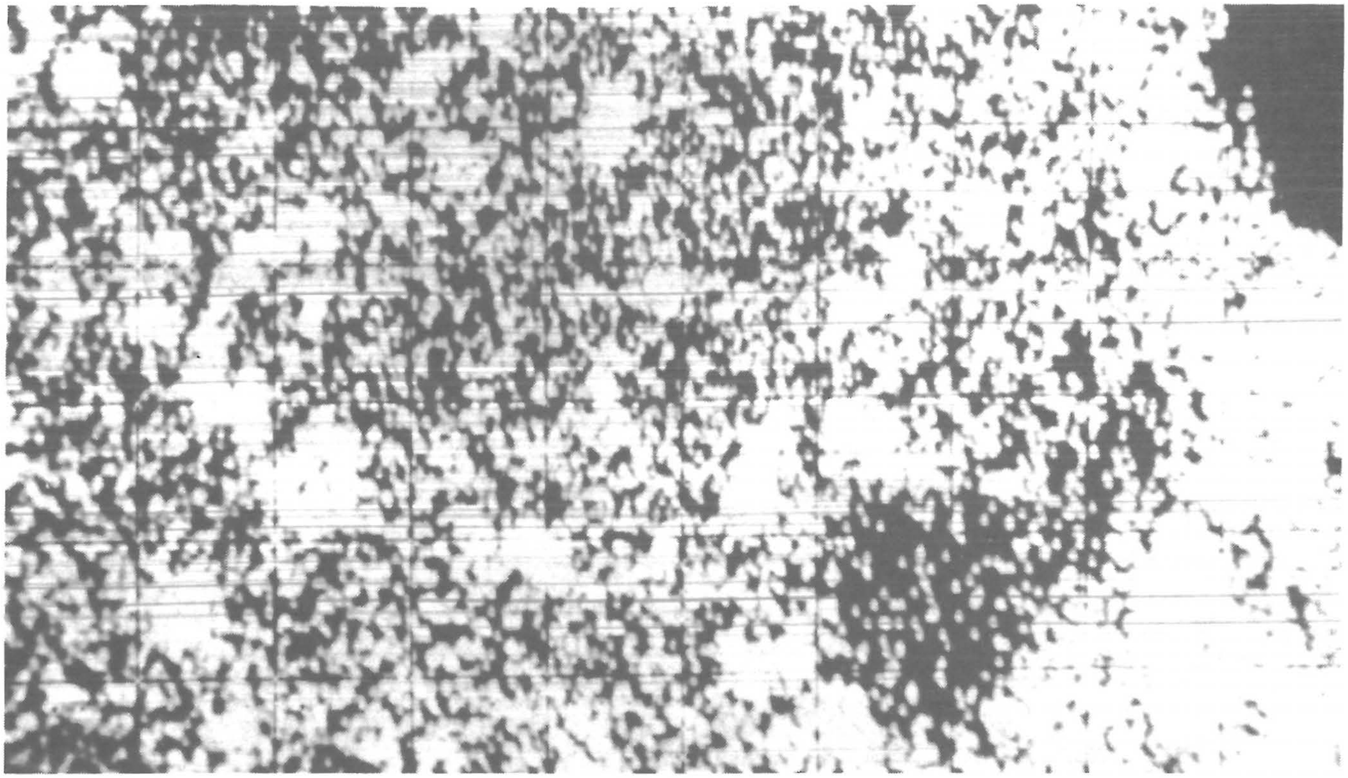

FIGURE 4. - Microprobe track revealing uneven potassium distribution. The dark, potassium-free areas are wax concentrations.

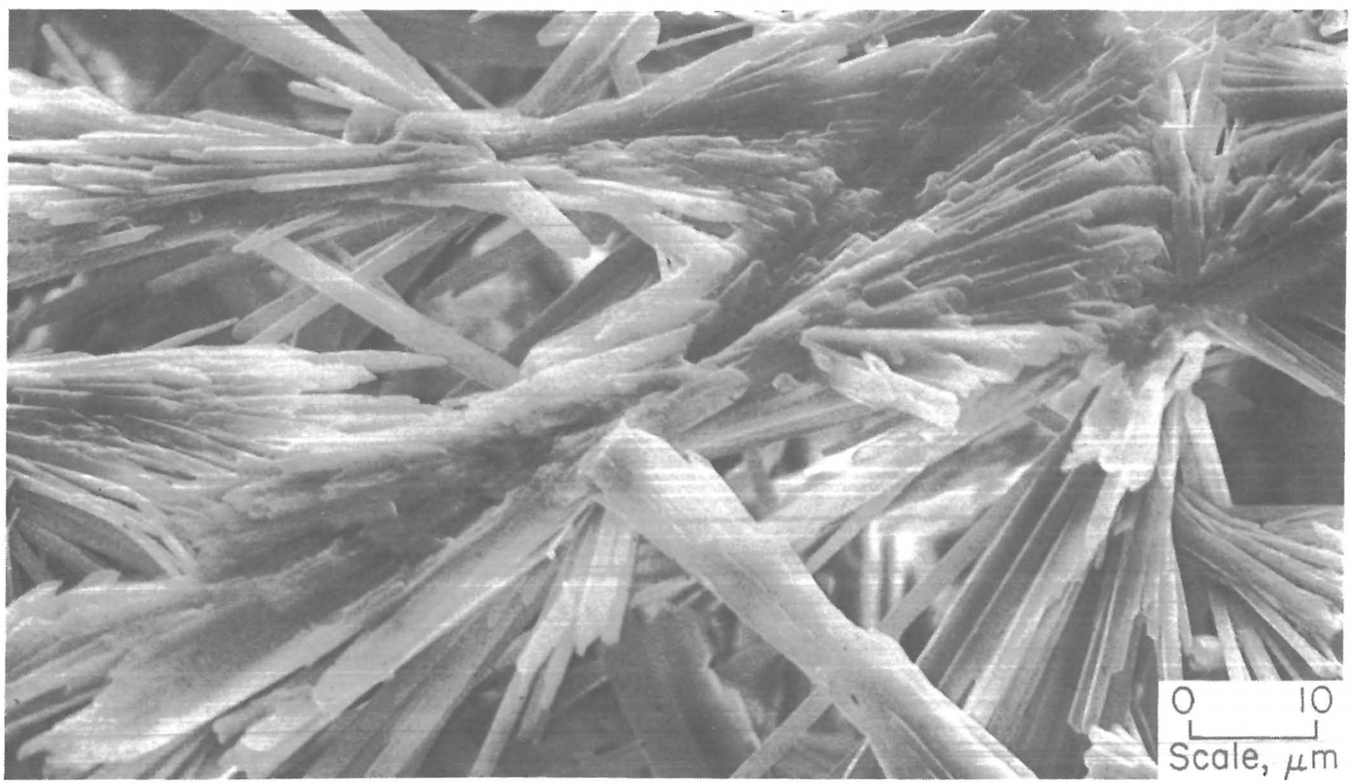

FIGURE 5. - SEM micrograph of undisturbed surface of gypsum cast at a 0.400 water-cement ratio and no accelerator.

manufactured and consisted of water that was encapsulated in a thin shell of paraffin wax that was modified for improved water retention. Figure 6 shows the capsules. The average water content was approximately 63.9 pct by weight. The accelerated plaster and water capsules were mixed in a V-blender, and the combined product was packed into a long plastic wrapper. Three different wrappers were used: 0.003-in polyethylene, 0.0014-in polypropylene, and 0.0010-in polypropylene-saran. All cartridges were nominally 0.97-in diameter, 23 in long, and sealed at each end. A sealed cartridge is shown in figure 7. Typically, the plaster and water capsules weighed 332 g. The wax from the water capsules occupied about 20 pct of the volume in the hardened grout.

BOLTS

Bolts were made from commercial rebar by threading one end of a 30-in length. Although all rebar met ASTM standard A 615 for grade 40 rebar,[9] the mechanical properties were not uniform because purchases were made from several lots. The average breaking load that was obtained from two rebars that were pulled was 44,150 lb, and the average yield load was 26,950 lb at 17 pct elongation. The respective minimum loads under the A 615 standard are 39,600 lb and 26,400 lb, and the minimum elongation is 12 pct. The ultimate loads sustained by the bolts were considerably less than the ultimate loads sustained by rebar because fracture occurred at the threads, which were reduced in cross sectional area at the minor diameter.

[9]Standard cited in footnote 8.

SIMULATED ROOF-BOLT HOLES

Simulated roof-bolt holes were made in materials having the compositions listed in table 1 by casting portland cement concrete and other cementitious mixtures in 4-in-diam pipes. One end of the pipe was capped with a 1/4-in-thick steel cover that had a hole for a core rod. Both 2- and 4-ft lengths were made. Cores for 2-ft-long holes were formed with a 1-1/32-in-diam rod that was located concentrically within the pipes.

FIGURE 6. - Capsules of water in wax shells.

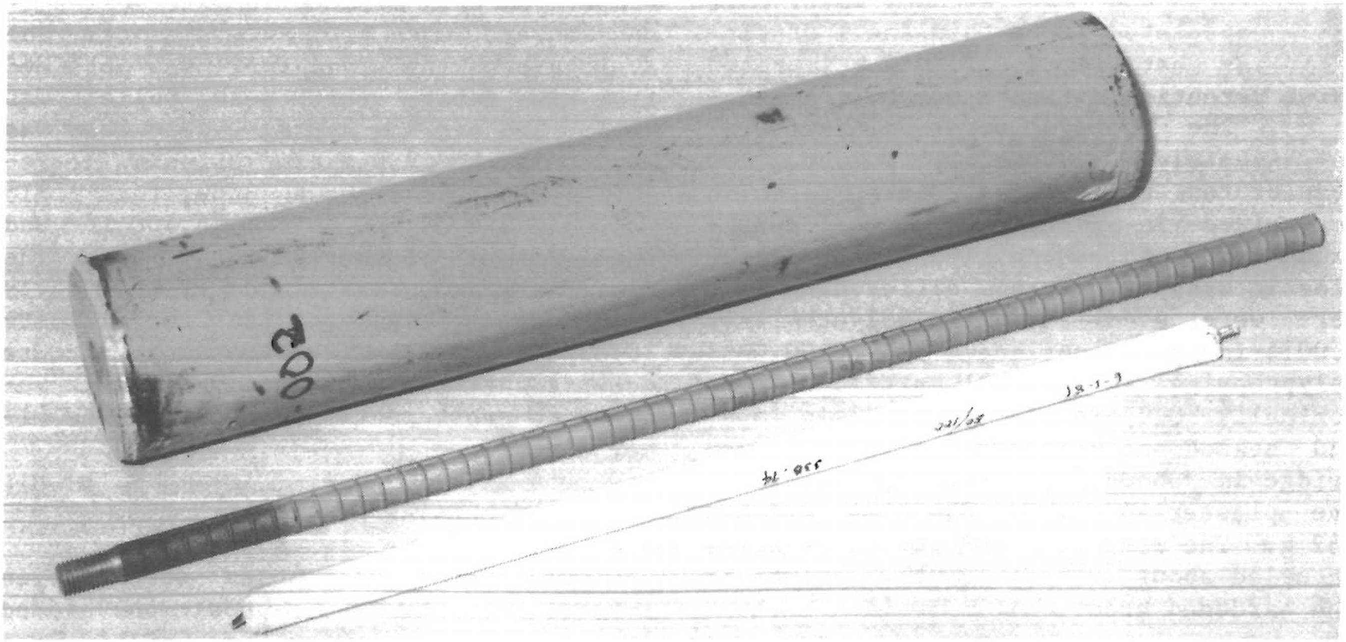

FIGURE 7. - Parts for a cartridge-type pull or creep specimen (1-1/32-in by 2-ft simulated bolt hole, 2-1/2-ft bolt, and plaster-water capsule cartridge).

TABLE 1. - Simulated roof-bolt hole mediums, percent

Concrete mix (by weight):		Coal mix (by volume):	
Cement	1	Crushed coal	10
Sand	2	Fly ash	8
Pea gravel	3.5	Cement	1
Water-cement ratio	.56	Water	3.5
Shale mix (by volume):		Plaster mix (by weight):	
Shale	10	Plaster	1
Fly ash	5	Water-cement ratio	.36
Cement	1		
Water	5		

The core rods were pulled after the concrete had set about 4 h, and the concrete was allowed to cure for a minimum of 28 days. No further operations were done on the holes. A 2-ft simulated hole, along with a bolt, is also shown in figure 7.

Four-foot-long holes were cored with a 5/8-in-diam rod and processed similarly to the 2-ft-long holes. Once cured, the 4-ft holes were bored to the 1-1/32-in diam. The bored hole surfaces were rougher than the cast hole surfaces.

INSTALLATION OF SIMULATED BOLTS

A unique hydraulic roof-bolt insertion machine, shown in figure 8, was used to install most of the 2-ft bolts for both pull and creep testing. The machine duplicated the actions of a commercial roof bolter except insertion was directed down rather than up. The insertion procedure differed depending on whether the cartridge-grouted bolting system or the slurry-grouted system was being simulated.

For slurry system simulation, a 2-ft simulated roof-bolt hole was clamped to the base of the machine, and a bolt was threaded into a rotatable sleeve that

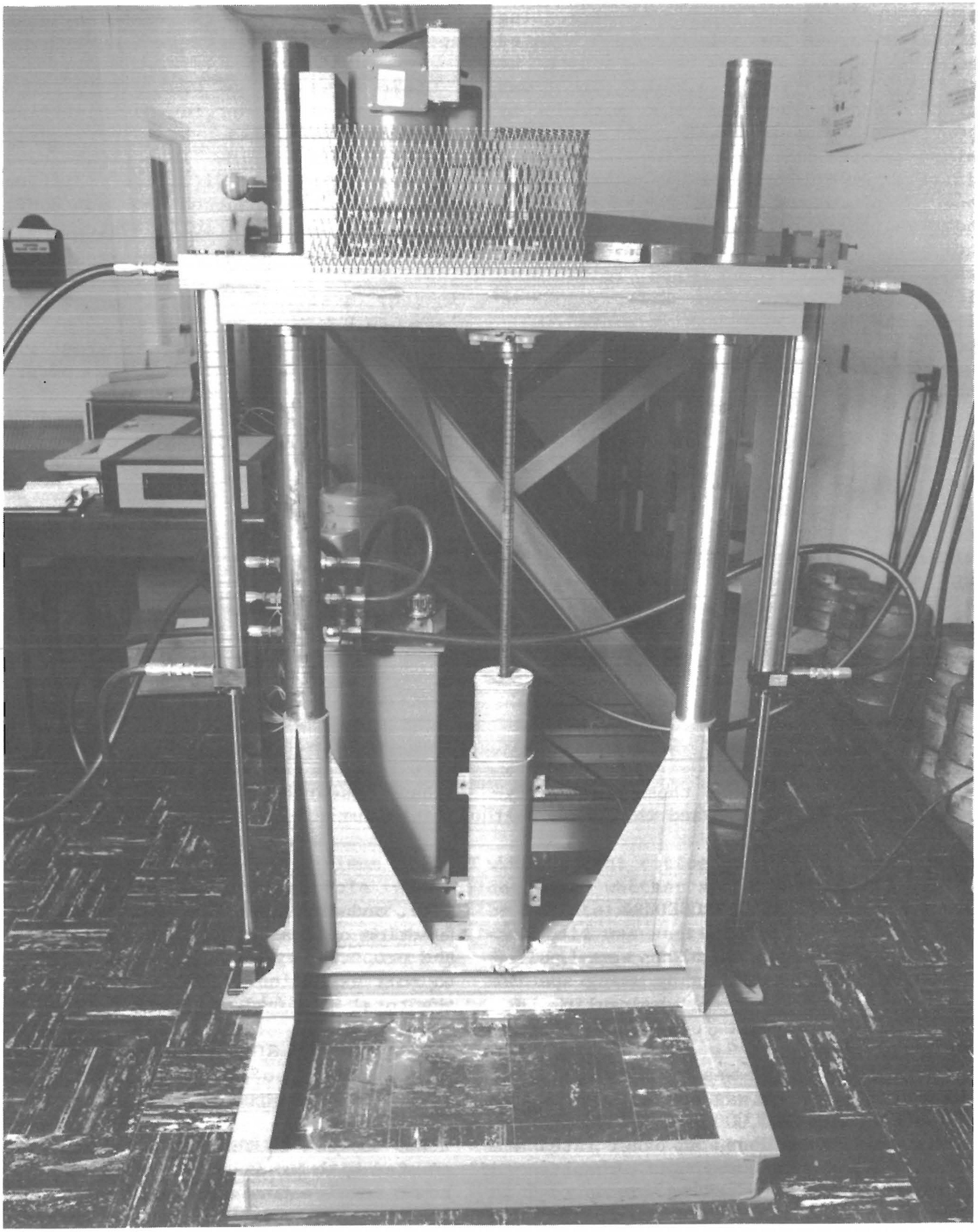

FIGURE 8. - Machine for inserting bolts in 2-ft simulated roof-bolt holes. Bolt insertion is directed downward.

was secured to the vertically traveling crosshead above the hole. The simulated hole was plugged with a rubber stopper at the end opposite insertion. Grout was mixed separately from the machine by pouring plaster into water in predetermined amounts and mixing for 10 s with a drill-motor-driven mixer. The grout was poured promptly in the hole, and the bolt was rotated and driven down into the hole via the crosshead. Little resistance was encountered, and bolts were installed in under 5 s. Either 360- or 154-r/min rotation rates were used. The rotation was discontinued when the bolt was inserted the entire length of the hole. The simulated hole with the roof bolt installed was left in place for the grout to set and then removed as a unit from the machine.

The simulation of cartridge-grouted roof bolts was done similarly. A 2-ft simulated hole and a bolt were installed in the machine, but instead of slurry, a cartridge containing the accelerated plaster and water capsule mix was placed in the hole. The bolt was rotated and driven down into the hole as before. Almost immediately, the cartridge wrapper ruptured, and the water capsules were crushed and mixed with the plaster as insertion proceeded. The rotation rates were the same as those for slurry-system-grouted bolts, and the hole-bolt combination was removed from the machine upon setting of the grout.

Greater resistance was usually encountered during insertion of cartridge-system-grouted bolts than slurry-system-grouted bolts. The insertions ranged from fairly easy to difficult. Difficult insertions were marked by an audible straining of the hydraulic system and, in extreme cases, by an inability to fully install the bolt for the entire 2-ft length. Insertion difficulties were related to how the cartridge wrapper broke up and to the degree to which grout pressure was relieved through loss of grout out the end. (The volume of grout contained in a cartridge was about 10 pct greater than the volume of a simulated hole containing a bolt.) Insertion durations ranged from 5 to 15 s.

All 4-ft installations were made with the cartridge system, but two 23-in cartridges for each bolt were used instead of one. The installation was accomplished with a commercial roof bolter using commercial roof bolts. All 2-ft bolts were installed at the Bureau's Albany (OR) Research Center, and all 4-ft bolts were installed at the Bureau's Spokane (WA) Research Center. All simulated bolts were pull- and creep-tested at the Albany Research Center.

PULL TESTS

PULL TEST PROCEDURE

The inserted roof bolts were pulled from the simulated holes by using special adaptors on a universal hydraulic test machine. A 2-ft bolt undergoing testing is shown in figure 9. With most tests, the loading rate was set initially at 60,000 lb/min, but was not maintained after a load of 10,000 to 15,000 lb was achieved. Tests done at other rates are noted in the discussion of results to follow. Bolts were pulled for up to 2 in unless the ultimate load was reached and forced the termination of the test. A deflectometer was used to measure the movement of a bolt from the simulated hole, and the movement was recorded as a function of load. Up to the yield point, the proportion of movement attributable to bolt extension was less than 5 pct of the total measured movement.

TWO-FOOT SIMULATED ROOF BOLTS

Grouted With Plaster Slurry

The bolts in this test series were grouted with premixed slurries containing 1 pct accelerator. The cure time, water-cement ratio, and simulated hole mediums were intentionally varied. (Cure time is defined as the period between bolt installation and pull testing.) An attempt

FIGURE 9. - Pull testing a 2-ft simulated roof-bolt system on universal hydraulic test machine.

was made to insure that the maximum grout possible was placed in a hole prior to the insertion of bolts. However, because the grout began setting within a few seconds after mixing and the setting inreased the viscosity, it was not always possible to fully grout all bolts. This was especially true with grouts made at water-cement ratios of less than 0.370. Thus, partial grouting occasionally became an unintentional variable.

Table 2 shows the results of pull tests with 2-ft simulated roof bolts that were grouted with plaster slurry. Cure times ranged from 10 min to 7 days. The normal water-cement ratio was 0.370 since this ratio most likely will be used with commercial bolters. Higher and lower water-cement ratios were investigated to determine whether adequate strength could be maintained within a usable range. Each bolt was sectioned after testing and the failure characteristics were noted. Failure occurred between either the grout and bolt or grout and hole wall.

At the normal water-cement ratio of 0.370, cure times equal to or greater than 10 min did not affect bolt load capacity. As exemplified by tests 1 through 3, no detectable movement occurred within the hole, and bolt fracture in the threaded portion was the cause of failure. Bolts cured for 1 h (tests 4 through 6) behaved similarly, and the tests were simply a measure of the strength of the rebar. Figure 10*A* shows

TABLE 2. - Pull test results on 2-ft simulated roof bolts grouted with plaster slurry

Test	Cure time	Hole construction	Total grout, g	Water-cement ratio	Max load, lb	Movement site[1]	Remarks
1...	10 min	Concrete.	Unk	0.370	37,550	No movement.....	Bolt broke.
2...	10 min	...do....	328	.370	37,100	...do...........	Do.
3...	10 min	...do....	314	.370	36,900	...do...........	Do.
4...	1 h...	...do....	325	.370	38,350	...do...........	Do.
5...	1 h...	...do....	349	.370	36,150	...do...........	Do.
6...	1 h...	...do....	335	.370	36,050	Slight, between grout and hole in upper 6 in.	Do.
7...	23 min	...do....	323	.400	36,750	No movement.....	Do.
8...	10 min	...do....	331	.400	31,350	Grout and bolt..	
9...	10 min	...do....	326	.400	30,100	...do...........	
10..	1 h...	...do....	326	.360	41,775	Slight, between grout and bolt in upper half.	Do.
11..	1 h...	...do....	252	.360	28,925	Grout and bolt..	Upper 9 in not completely grouted.
12..	1 h...	...do....	260	.360	14,750	...do...........	Partial grouting in many locations.
13..	1 h...	...do....	330	.360	32,250	Grout and hole, grout and bolt.	
14..	7 d...	Coal.....	322	.370	34,950	Grout and bolt..	
15..	7 d...	...do....	322	.370	25,350	Grout and hole..	
16..	7 d...	...do....	295	.370	36,900	...do...........	
17..	7 d...	Plaster..	311	.370	15,550	...do...........	
18..	7 d...	...do....	303	.370	12,000	...do...........	
19..	7 d...	Shale....	290	.370	9,250	...do...........	Upper 6 in not completely grouted.
20..	7 d...	...do....	316	.370	5,625	...do...........	
21..	7 d...	...do....	262	.370	2,825	...do...........	Partial grouting in many locations.
22..	7 d...	Concrete.	Unk	.370	36,740	No movement.....	Water passages; bolt broke.
23..	7 d...	...do....	341	.370	36,650	...do...........	Do.
24..	7 d...	...do....	Unk	.370	37,000	...do...........	Do.
25..	7 d...	...do....	325	.370	37,025	...do...........	Do.

Unk Unknown. [1]Upper hole is that portion nearest the bolt insertion end.

a typical load-versus-movement curve for all tests in which bolts were broken. The yield load occurred at 27,950 lb and the ultimate load at 37,550 lb. The average yield load for all slurry-grouted bolts was 27,600 lb.

When the water-cement ratio was raised to 0.400, the cure time became an independent variable. At a cure time of 23 min, as in test 7, the bolt failed similarly to bolts grouted at lower water-cement ratios, but at cure times of 10 min (tests 8 and 9), the bolts did not fail and the maximum load sustained was 31,350 lb. Movement occurred within the simulated hole between the bolt and grout; the rebar deformations on the bolt cut a core from the grout having the same circumference as the deformations. In comparing the movement of the bolt, as shown in figure 10*B*, with that in figure 10*A*, most movement of the bolt up to the point of the maximum load application resulted from bolt elastic elongation. However, movement of the bolt within the

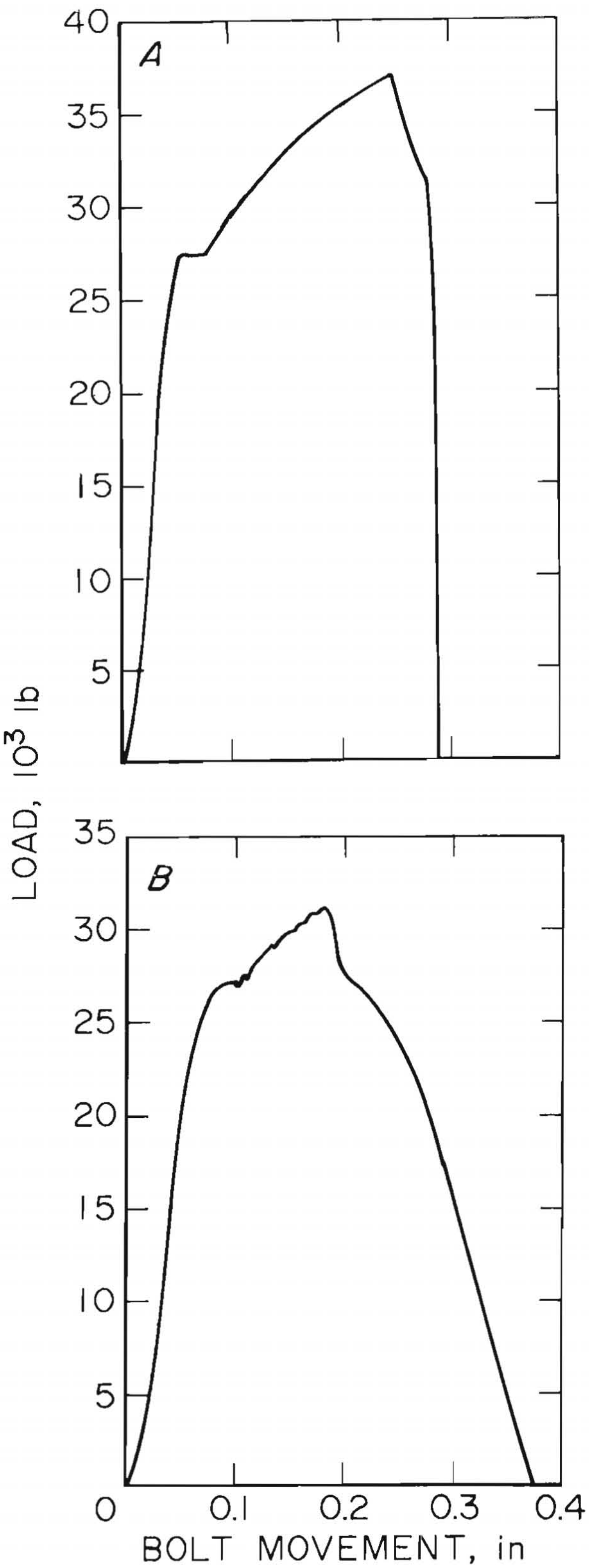

FIGURE 10. - Pull test results of typical plaster-slurry-grouted roof-bolt systems. *A*, 0.370 water-cement ratio (bolt broke); *B*, 0.400 water-cement ratio, 10-min cure time.

grout also occurred in nonuniforn increments up to this point. Thereafter, the strength of the bolt system decreased rapidly. Most movement between the maximum load application and the cessation of the test resulted from the movement of the bolt within the grout.

When the water-cement ratio was reduced to 0.360, difficulty was encountered in placing the grout in the simulated hole. Two of the four bolts used in tests 10, 11, 12, and 13 were undergrouted significantly and showed reduced strengths. Upon sectioning, one bolt was fully grouted in all but the top 9 in, while the other contained no fully grouted sections. The former sustained an acceptable load and was nearly twice as strong as the latter. These data indicate that strength is significantly reduced if all portions of the column are only partially grouted. (In this report, the upper hole is that portion nearest the bolt insertion end. The lower portion is at the opposite end.)

Although the bolt in test 13 was fully grouted for the 2-ft length, it was not broken and the load sustained was 9,500 lb less than obtained in test 10, in which the bolt was similarly grouted. The failure occurred primarily between the grout and hole wall, with secondary failure occurring between the bolt and grout. The fact that the simulated hole wall was unaccountably smoother than the others most likely is the reason for the reduced strength. As shown in figure 11, the load-carrying ability of the bolt system dropped initially after the yield strength was reached and increased thereafter. At least some of the increase may have resulted from frictional forces between the grout column and hole wall caused by a temperature rise. The total movement was excessive.

Three other hole mediums were tested. With all tests except one, failure occurred between the grout and hole wall and the load sustained was less than the loads sustained with concrete holes. The reduced strength reflects the weaker

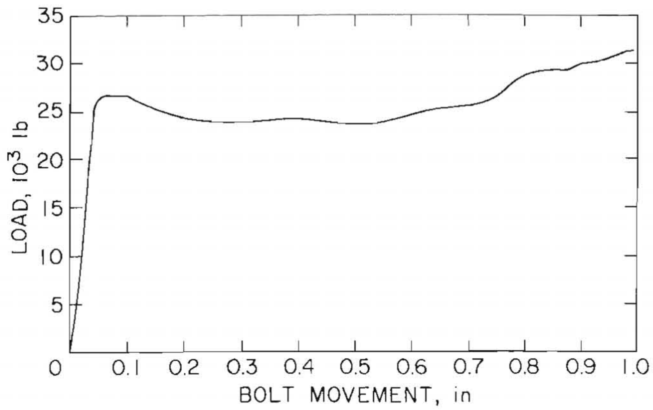

FIGURE 11. - Pull test result of a typical plaster-slurry-grouted roof-bolt system (test 13, 0.360 water-cement ratio). Smooth hole.

strength of the hole mediums. Bolt systems grouted in holes made with coal mix (tests 14 through 16) proved strongest, followed by bolt systems grouted in holes made with plaster (tests 17 and 18) and with shale (tests 19 through 21). The minimum pull test standard (17,700 lb) was not met with bolt systems grouted in holes made of the latter two mixes.

The remaining four tests reported in table 2 were done in an attempt to determine what effect mine waters seeping into or flowing past a gypsum-grouted bolt might have upon the ability of a bolt system to support a roof. In tests 22 through 24, eleven 3/8-in-diam holes, 4 to 5 in apart, were drilled to the grout-hole interface along radii immediately after the bolts were installed. Each test specimen was placed in 25 L of slightly agitated distilled water for 7 days prior to pulling, which allowed the water to contact the grout through the 3/8-in holes. The grout that dissolved at the end of the soaking period, determined by measuring the gypsum concentration in the water, was only 2.5 g, or less than 1 pct of the total grout. As shown in the table, the water and loss of grout were inadequate to cause even a slight decrease in strength, and all bolts broke at about 37,000 lb.

Another specimen was tested (25) under similar conditions except that the water was agitated more vigorously and exchanged four times at 1-day intervals. The specimen lost 7.5 g of grout, which also had no effect upon strength.

In summary, the tests predict that at water-cement ratios of 0.360 to 0.400, slurry-grouted roof bolt systems can provide more than adequate roof strength in as little as 10 min. However, two qualifications must be met: (1) A bolt must be fully grouted along a portion of its length (the lower limit is less than 15 in but has not been determined exactly), and (2) the hole that supports the grouting medium must contain rock of sufficient strength. The long-term effects of static water on the bolt system strength were not adequately determined.

Grouted With Plaster-Water Capsule Mix Encased In 0.003-In Polyethylene Wrappers

Pull tests were conducted on a series of bolts that were installed using 23-in cartridges. The cartridge contents, consisting of the plaster-water capsule mix, were encased in sealed wrappers made with 0.003-in-thick polyethylene plastic. Each cartridge contained wax-encased water capsules at a ratio of 0.500, by weight, to the plaster, which provided a water-to-plaster ratio of 0.319. The wax accounted for about 20 pct of the volume in the hardened gypsum after insertion. The plaster contained 1 pct K_2SO_4 accelerator.

Table 3 shows the results of pull tests in which the only parameter that was intentionally varied was the cure time. However, during the course of testing, several other parameters that were uncontrollable were revealed. For example, it was impossible to retain the entire cartridge contents within the hole during installation, and the average loss of grout material was about 40 g. Although the effect was not determined precisely, in the extreme this undergrouting was detrimental and should be considered a variable.

TABLE 3. - Pull test results on 2-ft simulated roof bolts grouted with plaster-water capsule mix encased in 0.003-in polyethylene wrappers

(Conditions: 0.319 water-cement ratio, 0.500 capsule-plaster ratio, concrete holes, 360-r/min rotation)

Test	Cure time	Total grout, g	Max load, lb	Movement site[1]			Wrapper disposition
				Grout-bolt	Grout-wrapper	Wrapper-hole	
26..	10 min	302	33,800	Upper 9 in..	Lower 15 in.	None........	Intact, lower 18 in.
27..	10 min	268	24,500	Upper 10 in.	None........	Lower 14 in.	Intact, lower 15 in.
28..	10 min	295	32,725	None........	Whole length	None........	Intact, lower 19 in.
29[2].	1 h...	Unk	27,285	Unknown.....	Unknown.....	Unknown.....	Intact, lower 18 in.
30..	1 h...	Unk	27,760	Upper 8 in..	Lower 16 in.	None........	Intact, lower 12 in.
31..	1 h...	299	27,250	Upper 6 in..	Lower 18 in.	...do.......	Intact, lower 18 in.
32..	1 h...	274	27,700	Upper 4 in..	Lower 20 in.	...do.......	Intact, lower 19 in.
33..	1 h...	282	29,650	Upper 14 in.	Lower 10 in.	...do.......	Intact, lower 15 in.
34[3].	7 d...	304	34,700	Unknown.....	Unknown.....	Unknown.....	Unknown.
35..	7 d...	307	35,675	Upper 10 in.	Lower 14 in.	None........	Intact, lower 14 in.
36..	7 d...	261	24,175	Upper 7 in..	Lower 17 in.	...do.......	Intact, lower 17 in.

Unk Unknown.
[1]Upper hole is that portion nearest the bolt insertion end.
[2]Inserted 20 in.
[3]Grip broke.

Sectioning of the tested specimens revealed two additional factors that undoubtedly accounted for a portion of the scatter in the results. In nearly all specimens, the wrapper did not disperse throughout the grout, but instead was retained intact between the grout and hole wall. The wrapper was usually dispersed in the upper portion of the hole, but the dispersed length varied. A third factor that should be regarded as an unintentional variable is the site at which movement occurred.

Because the length of the intact bag varied, the site of movement also varied. Movement generally occurred between the grout and the bolt in the upper portion of the specimen. This is the portion in which the bag was dispersed. In the lower portion of the specimen, movement occurred between the grout and the wrapper, that is, the grout column moved with the bolt. Since the upper grout was stationary, it acted as a collar against which the lower grout was compressed. Figure 12 shows a sectioned bolt after pull testing, clearly revealing the intact wrapper in the lower portion of the simulated hole. The wrapper is twisted around the bolt in the upper portion. Little grout has adhered to the hole wall in the lower portion, while in the upper portion the grout is firmly attached.

Table 3 shows that after 10 min, the lowest practical cure time, ample load-carrying capacity was achieved. Disregarding test 27, which suffered from excessive undergrouting, the average maximum load sustained in tests 26 and 28 was 33,263 lb. The load is 4,000 or more pounds less than the load sustained by slurry-grouted bolt systems that contained water at a 0.360 water-cement ratio.

Tests 26 and 28 had similar maximum loads; however, the movement sites were different. Movement in 26 occurred both between the grout and bolt, and between the grout and wrapper, while movement in 28 occurred only between the grout and wrapper. The difference is reflected in the curves that express load versus movement. With 26, the load was maintained above 25,000 lb throughout the test, but in 28, the load steadily declined. Curves for both are shown in figure 13. The data suggest that the less desirable bolt systems are those in which shear between the wrapper and grout is entirely responsible for load-carrying capacity. Comparisons between the data shown in figures 13*A* and 13*B* show that greater sustained capacity is achieved when shear occurs between the bolt and grout along a portion of the anchored length.

FIGURE 12. - Section of pull-tested, cartridge-installed roof-bolt system. Cartridge wrapper is dispersed in upper one-fourth of simulated hole and intact in remainder.

After a 1-h cure (tests 29 through 33), an average ultimate load capacity of 27,929 lb was obtained. The capacity is nearly 5,000 lb less than the capacity of bolts pulled after only a 10-min cure time. The factor that most likely accounts for the reduction in load-carrying capacity is that accelerated gypsum is weaker at 1 h than at 10 min. In compression tests on 2-in cubes, accelerated gypsum was found to experience an initial peak strength after a cure time of about 10 min. Figure 14 shows the behavior of the 2-in cubes.

After 7 days, the gypsum in the grout experienced considerable drying and was substantially stronger. The average load capacity at 7 days, as exemplified

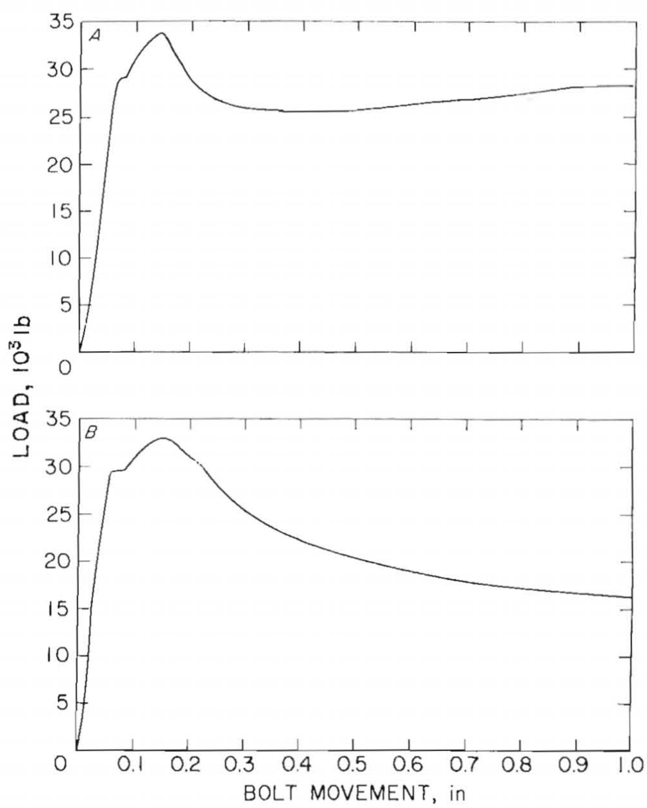

FIGURE 13. - Pull test results of cartridge-grouted roof-bolt systems (0.319 water-cement ratio, polyethylene wrapper). *A*, (Test 26) bolt movement between both grout and bolt, and grout and wrapper; *B*, (test 28) bolt movement between grout and wrapper only.

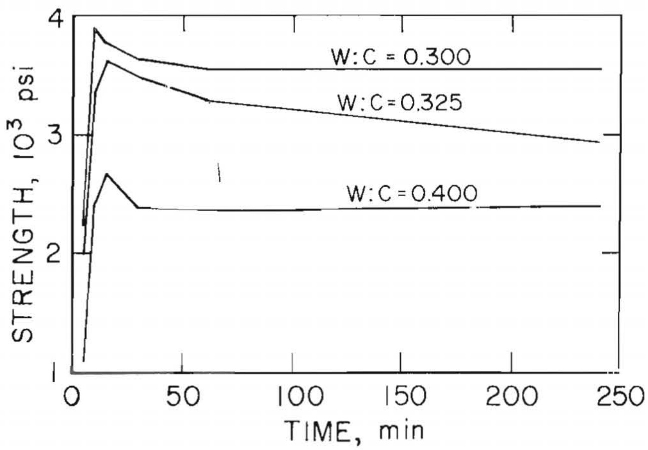

FIGURE 14. - Compressive strength variation of accelerated gypsum from time of hydration with varying water-cement (W:C) ratios.

by tests 34 and 35, was 35,188 lb. The load-versus-movement curves for these tests, as well as the bolts pulled after 1 h of curing, were similar to the curve of test 26, as shown in figure 13*A*. Undergrouting caused the load capacity of another bolt (test 36), which was cured for 7 days, to be decreased by more than 10,000 lb.

With most bolts, sectioning showed two types of grout. The greatest proportion of grout had an appearance similar to cast gypsum but in which the remnants of wax capsules appeared as discrete islands. In small areas, generally located in the lower simulated hole section, the grout was shiny and waxlike. The surface of the shiny grout, in addition to appearing fused, often contained striations parallel to the axis of bolt movement. SEM examination showed an absence of crystal structure in the shiny grout and indicates that under pressure (and perhaps temperatures sufficient for melting), the wax diffuses more thoroughly into the gypsum. Figure 15 shows the various structures obtained with cartridge-grouted specimens.

In general, sufficiently high load capacities can be achieved by bolt systems with cartridges encased in 0.003-in polyethylene wrappers at cure times of 10 min or longer. The capacities may be adversely affected by the wax capsules, the wrapper, the position of the wrapper, or a combination of these factors. Load capacity is also adversely affected by undergrouting, but even undergrouted specimens have load capacities well in excess of the minimum required load capacity (17,700 lb). The presence of the wrapper between the grout and hole wall shifts the site of movement during loading from the grout-bolt interface to the grout-wrapper interface.

Grouted Under Unusual Conditions With Plaster-Water Capsule Mix Encased In 0.003-In Polyethylene Wrappers

A series of pull tests was conducted on bolts that were installed to determine limiting conditions or to investigate the effects of additional variables on load capacity. The results are shown in table 4 and can be compared with an average load capacity of 27,929 lb for a cartridge-grouted bolt system installed under normal conditions and cured for 1 h. In tests 37 through 39, the water-cement ratio was lowered to 0.288 from 0.319 by reducing the proportion of capsules added to the grout. The average load capacity was 37,333 lb and nearly 10,000 lb greater than the average capacity of bolt systems installed at the higher water-cement ratio. This load capacity approaches the ultimate strength of the bolt, and the load capacity obtainable with slurry-grouted bolt systems. Less grout was lost during insertion probably because the plaster hardened faster and produced a better seal. The viscosity also increased and made insertion more difficult. The wrappers remained intact to the same degree, but the movement site was shifted, and a greater proportion of movement occurred between the grout and bolt rather than the grout and wrapper. The loads were maintained throughout the test similarly to that typified in figure 13*A*.

The bolt of test 40 was pulled past its maximum load capacity (1/2 in) and then relaxed. After 45 min, the test was resumed at the same loading rate and continued until a total of 2 in of movement occurred. As shown in figure 16, the

TABLE 4. - Pull test results on 2-ft simulated roof bolts grouted under unusual conditions

(Conditions: Plaster-water capsule mix encased in 0.003-in polyethylene wrappers, 0.319 water-cement ratio except as noted, 0.500 capsule-plaster ratio except as noted, 1-h cure time except as noted, concrete holes, 360-r/min rotation)

Test	Total grout, g	Max load, lb	Movement site[1]			Wrapper disposition	Remarks
			Grout-bolt	Grout-wrapper	Wrapper-hole		
37..	304	36,800	Upper 6, lower 13 in.	From 6 to 11 in.	None....	Intact, lower 20 in.	0.288 water-cement ratio; 0.45 capsule-plaster ratio.
38..	314	36,250	Upper 9, lower 13 in.	From 9 to 11 in.	...do...	...do........	Do.
39..	330	38,950	Upper 4, lower 12 in.	From 4 to 12 in.	...do...	Intact, lower 19 in.	0.288 water-cement ratio; 0.45 capsule-plaster ratio; difficult insertion.
40..	309	31,150	Upper 11 in.	Lower 13 in.	...do...	Intact, lower 18 in.	Pulled 1/2 in, stopped 45 min, pulled 1-1/2 in more.
41..	303	29,150	Whole length.	None......	...do...	No wrapper...	Grout mix only in hole.
42[2].	314	34,150	...do...	...do.....	...do...	...do........	Do.
43[2].	Unk	26,225	...do...	...do.....	...do...	...do........	Do.
44[2].	Unk	28,725	...do...	...do.....	...do...	...do........	Undergrouted upper 9 in; grout mix only in hole; voids at several locations.
45..	282	14,650	Upper 6 in.	...do.....	Lower 18 in.	Intact, lower 18 in.	Slurry poured into wrapper.
46..	276	13,475	None....	...do.....	Whole length.	...do........	Do.
47[2].	309	26,150	...do...	Whole length.	None....	Intact, lower 23 in.	Slurry in sealed wrapper; no accelerator.
48..	318	35,125	Whole length.	None......	...do...	Intact, lower 13 in.	Sausage-link cartridge.
49..	262	27,600	...do...	...do.....	...do...	Intact, lower 17 in.	Do.
50..	319	31,450	Upper 10 in.	Lower 14 in.	...do...	Intact, lower 14 in.	Wet hole.
51..	240	27,000	Upper 18 in.	Lower 6 in.	...do...	Intact, lower 6 in.	Wet hole, undergrouted.
52..	245	20,150	Upper 6 in.	Lower 18 in.	...do...	Intact, lower 18 in.	Do.

Unk Unknown.
[1]Upper hole is that portion nearest the bolt insertion end.
[2]1-day cure time.

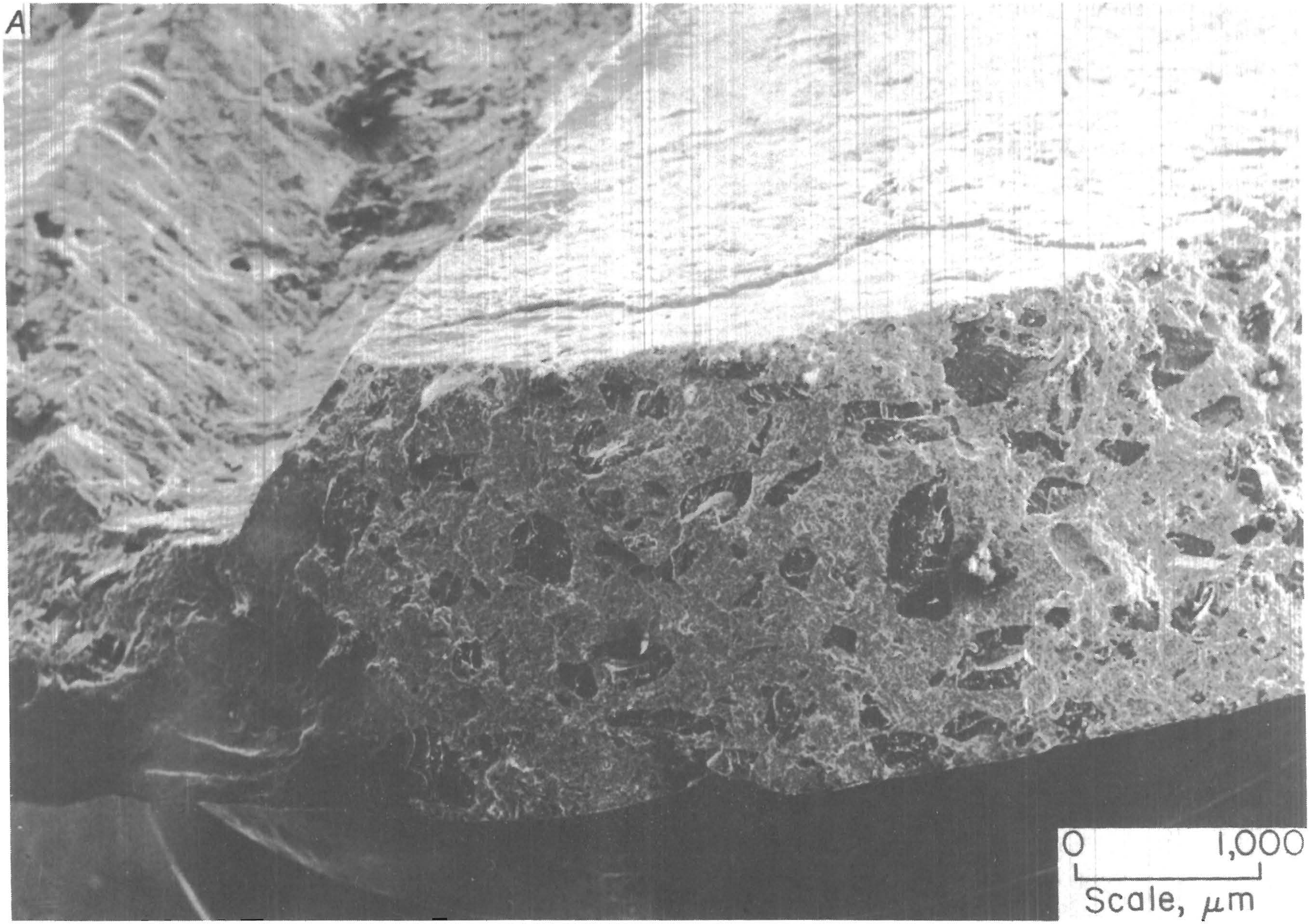

FIGURE 15. - Grout obtained from a pull test specimen. *A*, Dark islands are remnants of wax capsule.

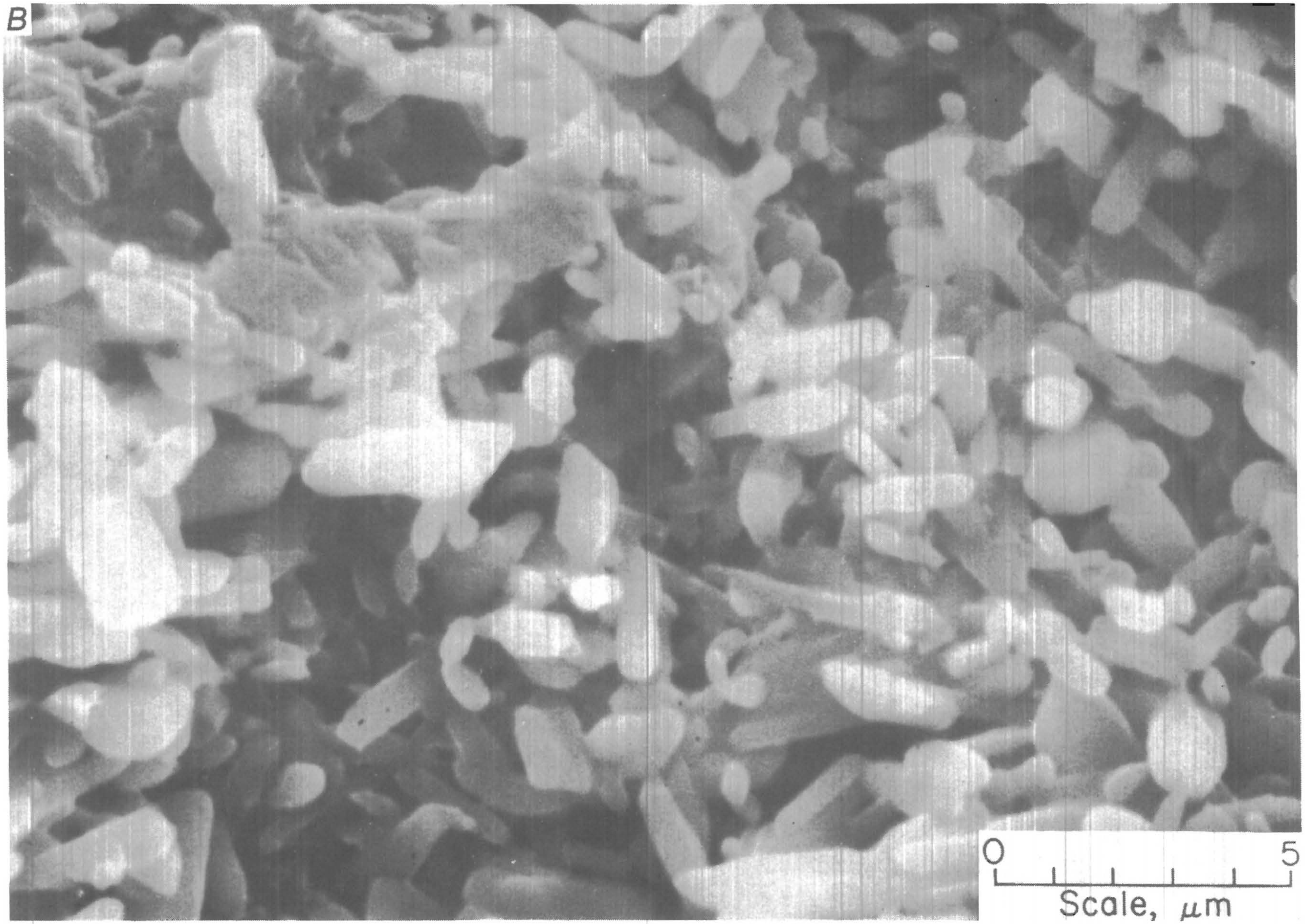

FIGURE 15. - Grout obtained from a pull test specimen—Continued. *B*, Gypsum has a castlike structure.

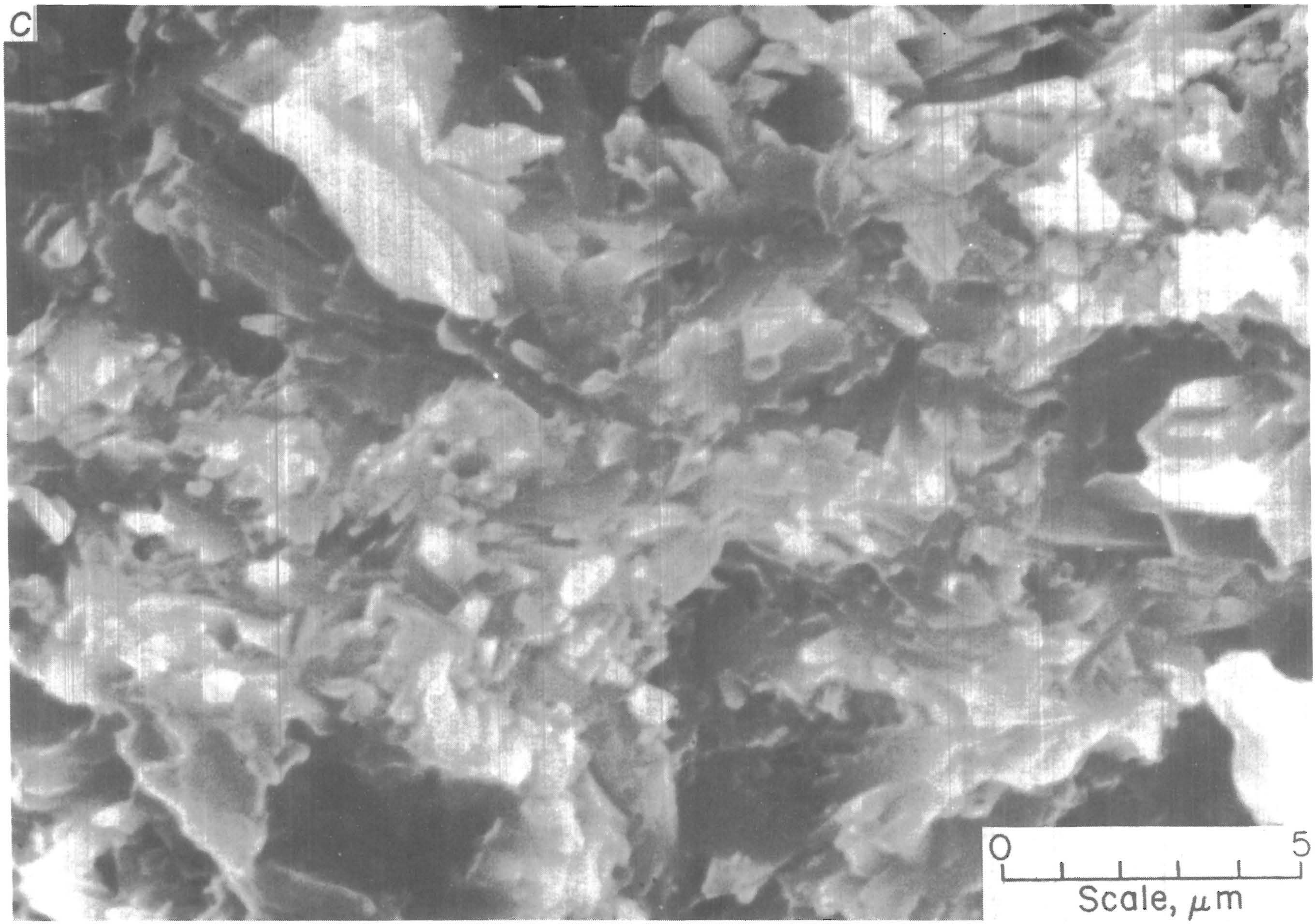

FIGURE 15. - Grout obtained from a pull test specimen—Continued. *C*, Gypsum crystal structure is obscured by wax diffusion.

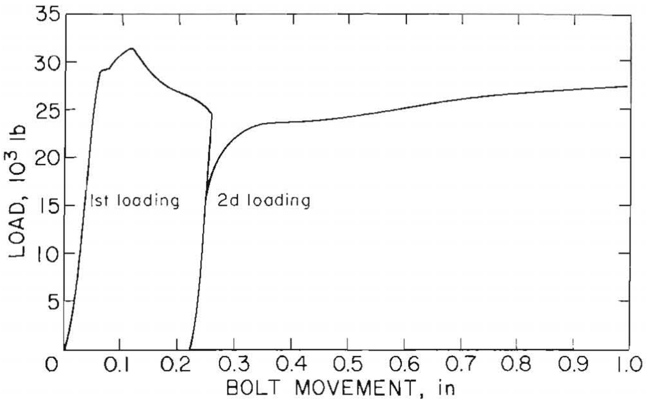

FIGURE 16. - Pull test result of cartridge-grouted roof-bolt system (test 40). Two loadings with 45-min relaxation period in between.

load decreased after the maximum at 31,150 lb was reached. The negative movement resulted from the elasticity in the bolt steel. Upon the second loading, the bolt elasticity was taken up, and movement proceeded at load levels consistent with tests in which bolts experienced only one loading. It appears that bolt systems will behave the same regardless of cyclic loadings and that movement within the grout is inelastic.

A number of differences between the slurry-grouted system and the cartridge-grouted system could account for the disparity in load capacities between the two systems. However, the presence and position of the cartridge wrapper and the presence of wax capsules are the two most prominent factors. Several attempts were made to exclude one or the other to determine if one factor was more predominant than the other. Grout mix containing water capsules and plaster in a 0.500 ratio were placed in simulated holes without wrappers, and the bolts were inserted and pulled. Tests 41 through 44 (table 4) showed a fairly wide variability but, on the average, slightly higher load capacity than that of cartridge-grouted bolt systems. This suggests that the wrapper contributes only marginally to the reduction of load capacity, perhaps by the transference of the movement site.

The wax capsules were excluded from a cartridge but the wrapper was retained in an additional set of specimens that were designed to isolate the effect of the wrapper (table 4, tests 45, 46, and 47). Presumably, load capacities should have risen substantially. In tests 45 and 46, 18-in-long wrappers were placed in simulated holes and plaster slurry was poured in the hole just prior to bolt insertion. The pull test load capacities were roughly half of the average 1-h load capacities of bolt systems installed with regular cartridges. Sectioning revealed that sufficient hydraulic pressure during installation had not been generated within the grout. The wrapper had not been forced against the sides of the simulated hole; instead the interface between the wrapper and hole wall was loose. To overcome this problem, unaccelerated plaster slurry was poured into a wrapper and sealed to make the specimen for test 47. Before the bolt was inserted, the grout was cured 7 min to raise its viscosity and thereby raise the hydraulic pressure within the hole. The load capacity was 26,150 lb, which is only 6 pct less than the average load capacity of a cartridge-grouted bolt system installed under normal conditions. Test 47 and prior tests would indicate that neither the wax capsules nor the wrapper is responsible for the reduction in load capacity of cartridge-grouted bolt systems, but such a conclusion is implausible. It is more likely that the events and conditions that occur in combination during bolt insertion with cartridges cannot be duplicated separately. It should be noted, however, that intact wrappers are found in test specimens that have been grouted with commercial cartridges containing polyester resin. The pull test loads of these specimens are consistently in excess of the bolt breaking strength. By analogy, the wrapper in the plaster-grouted specimens would appear to be blameless in lowering bolt capacity.

In another series of tests, an attempt was made to cause the wrapper to break up and disperse more. A 23-in cartridge was tied with heavy string at 6-in intervals in the fashion of sausage links (test 48). Unfortunately, the cartridge could not be completely constricted at the tie-off locations by using this technique, and the tie-offs were only partially effective in promoting wrapper dispersal. Nevertheless, the load capacity increased substantially to 35,125 lb, and the movement site was confined to the grout-bolt interface.

A second sausage-link-type cartridge was also made by loading the grout mix into each link separately after each previous link had been tied (test 49). While the constriction at each tie-off location was complete, the arrangement reduced the wrapper capacity and undergrouting occurred. Moreover, the tie-offs were again unsuccessful in preventing the wrapper from locating between the grout and hole wall. As with the first sausage-link cartridge, the movement site was shifted to the grout-bolt interface, and a surprisingly high load capacity was achieved, considering the degree of undergrouting.

Tests 50 through 52 were made to determine the effects that installation into a wet hole might have. Concrete holes were soaked 7 days prior to insertion. Test 50 had above average load capacity, but tests 51 and 52 were undergrouted and had below average load capacities. No differences were noted during section analysis between bolts installed in either dry or wet simulated holes.

Although many of the purposes for the tests in tables 3 and 4 are different, 12 bolts were installed with cartridges having a 0.319 water-cement ratio and a 1-h curing time. The total grout contained in 10 of these tests is known. Figure 17 shows the dependence of load capacity upon the quantity of grout anchoring the bolts in these 10 tests. In all cases, the bolt systems surpassed the minimum standard (17,700 lb). However, load capacity dropped off substantially if a bolt had less than 260 g of grout as an anchoring medium. With more than 260 g, the data show that a bolt system can still be undergrouted if voids are evenly dispersed, but it is only when the voids are located at an end and the remaining grout is voidless that less than normal grouting will not result in weak load capacities.

Grouted With Plaster-Water Capsule Mix Encased In 0.0014-In Polypropylene Wrappers

In another attempt to promote greater breakup of wrappers and improve the load capacities, cartridges were produced with thinner and weaker wrappers made of polypropylene. The plaster-water capsule mix was unchanged, and the insertion procedure remained the same except that some bolts were installed at a slower rotation speed. Although more consistent with commercial bolters, the slower rotation speed had a negligible effect. The results of pull tests on bolts installed with grouts encased in the 0.0014-in wrappers are shown in table 5. These wrappers failed to disperse any more than the 0.003-in polyethylene wrappers. In general, the results were more scattered and unpredictable, and the movement site in the lower section of the bolt system was between the wrapper and hole, whereas movement occurred between the grout and wrapper in most of the tests in which the polyethylene wrappers were used.

The polypropylene wrapper was slicker than the polyethylene wrapper, which may account for the greater loss of grout during installation. From table 3, the average known total grout contained in

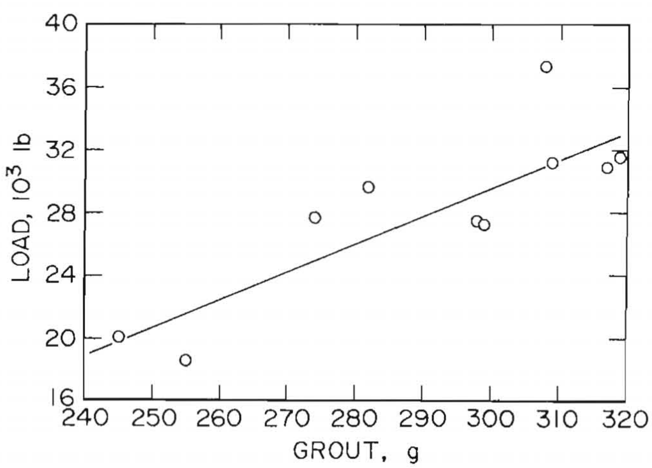

FIGURE 17. - Dependence of load capacity upon grout content of cartridge-grouted roof-bolt systems.

tests with polyethylene wrappers was 288 g. The average total grout contained in the first eight tests listed in table 5 was 265 g. However, the reduced amount of grout did not decrease the pull test load capacity from the average registered by specimens with polyethylene wrappers. After the first eight tests, the bolts of the remaining specimens were installed using a device that succeeded in retaining most of the grout within the hole. The variance in load capacity did not improve with the device. As shown in table 6, the coefficient of variation in load capacity without the device was 20.1 pct, while with the device the coefficient of variation was 26.0 pct.

The average load capacity was 27,442 lb after a 1-h cure; 23,555 lb after a 1-day cure; and 33,675 lb after a 7-day cure. Test 69 was excluded from the 7-day average because the cylinder cracked during installation and much grout oozed into the crack. No explanation was apparent for the decline in load capacity after 1 day, but the reproducibility was poor, and the data are thus relatively unreliable. The load capacities at 1 h and 7 days of the bolt system installed with cartridges that were encased in the 0.0014-in polypropylene wrappers was roughly equivalent to the capacities of bolt systems cured similarly and installed with cartridges that were encased in 0.003-in polyethylene wrappers. The loads were not maintained, as typified by the load-movement curve of figure 18; the load fell below 20,000 lb at 0.6 in of movement. In contrast, the load capacity, as shown in figure 13*A*, for a bolt system installed with cartridges containing 0.003-in wrappers was maintained above 20,000 lb.

Grouted With Plaster-Water Capsule Mix Encased In 0.0010-In Polypropylene-Saran Wrappers

A 0.0010-in wrapper made of polypropylene and saran also failed to disperse significantly more than the 0.003- or

TABLE 5. - Pull test results on 2-ft simulated roof bolts grouted with plaster-water capsule mix encased in 0.0014-in polypropylene wrappers

(Conditions: 0.319 water-cement ratio; 0.500 capsule-plaster ratio; concrete holes; tests 44-53 at 360 r/min, remainder at 154-r/min rotation)

Test	Cure time	Total grout, g	Max load, lb	Movement site[1]		Wrapper disposition
				Grout-bolt	Wrapper-hole	
53.......	1 h...	271	34,275	Whole length..	None........	Intact, lower 15 in.
54.......	1 h...	262	19,850	Upper 4 in....	Lower 20 in.	Intact, lower 20 in.
55.......	1 h...	252	25,000	Upper 10 in...	Lower 14 in.	Intact, lower 12 in.
56.......	1 h...	256	22,175	...do.........	...do.......	Intact, lower 10 in.
57.......	1 h...	276	31,200	...do.........	...do.......	Intact, lower 6 in.
58.......	1 h...	252	22,475	Whole length..	...do.......	Intact, lower 10 in.
59.......	1 h...	286	35,450	Upper 12 in...	Lower 12 in.	Intact, lower 20 in.
60.......	1 h...	264	28,125	Upper 4 in....	Lower 10 in.	Intact, lower 21 in.
61[2]......	1 h...	301	28,425	Upper 13 in...	Lower 11 in.	Intact, lower 14 in.
62[2]......	1 d...	332	16,375	Upper 8 in....	Lower 16 in.	Intact, lower 15 in.
63[2]......	1 d...	309	33,100	Upper 9 in....	Lower 13 in.	Intact, lower 16 in.
64[2]......	1 d...	315	20,875	Unknown.......	Unknown.....	Intact, lower 17 in.
65[2]......	1 d...	289	24,275	Whole length..	None........	Intact, lower 18 in.
66[2]......	1 d...	332	23,150	Upper 14 in...	Lower 10 in.	Do.
67[2]......	7 d...	332	34,900	Whole length..	None........	Dispersed.
68[2]......	7 d...	330	32,450	...do.........	...do.......	Intact, lower 13 in.
69[2,3]....	7 d...	332	13,400	Unknown.......	Unknown.....	Unknown.

[1]Upper hole is that portion nearest the bolt insertion end. No movement noted between the grout and wrapper.
[2]Grout retention device used. [3]Hole cracked.

TABLE 6. - Average pull test results for all systems

Cure time	Water-cement ratio	Load, lb	Number of tests	Coefficient of variation, pct
SLURRY				
10 min.	0.370	37,183	3	[1]0.9
1 h....	.370	36,850	3	[1]3.5
7 d....	.370	36,854	4	[1].5
0.003-In POLYETHYLENE CARTRIDGE				
10 min.	0.319	30,341	3	16.8
1 h....	.319	27,929	5	3.5
7 d....	.319	31,517	3	20.2
1 h....	.288	37,333	3	3.8
0.0014-In POLYPROPYLENE CARTRIDGE				
1 h....	0.319	27,442	9	20.1
1 d....	.319	23,555	5	[2]26.0
7 d....	.319	33,675	2	[2]5.1
0.0010-In POLYPROPYLENE-SARAN CARTRIDGE				
1 h....	0.319	29,560	5	12.7
1 d....	.319	26,935	5	22.7
FASLOC CARTRIDGE				
1 d....	Resin	37,533	3	[1]0.8

[1]All bolts broke.
[2]Grout retention device was used.

TABLE 7. - Pull test results on 2-ft simulated roof bolts grouted with plaster-water capsule mix encased in 0.0010-in polypropylene-saran wrappers

(Conditions: 0.319 water-cement ratio, 0.500 capsule-plaster ratio, concrete holes, 154-r/min rotation)

Test	Cure time	Total grout, g	Max load, lb	Movement site[1]: Grout-bolt	Movement site[1]: Grout-wrapper	Movement site[1]: Wrapper-hole	Wrapper disposition
70..	1 h.	310	34,800	Whole length.	None.........	None........	Intact, lower 18 in.
71..	1 h.	282	24,550	...do........	...do........	...do.......	Dispersed.
72..	1 h.	325	29,950	Upper 15 in..	...do........	Lower 9 in..	Intact, lower 9 in.
73..	1 h.	328	27,875	...do........	...do........	...do.......	Intact, lower 15 in.
74..	1 h.	298	30,625	Upper 12 in..	...do........	Lower 12 in.	Intact, lower 6 in.
75[2].	1 d.	332	20,425	Upper 7 in...	...do........	Lower 17 in.	Intact, lower 12 in.
76..	1 d.	332	36,200	Whole length.	...do........	None........	Unknown.
77..	1 d.	316	26,175	Upper 4 in...	Lower 20 in..	...do.......	Intact, lower 19 in.
78..	1 d.	294	22,925	Upper 8 in...	Lower 16 in..	...do.......	Intact, lower 10 in.
79..	1 d.	324	28,950	Whole length.	None.........	...do.......	Unknown.

[1]Upper hole is that portion nearest the bolt insertion end.
[2]Last 6 in not installed.

0.0014-in wrappers. As shown in table 7, the load capacity after 1 h curing time was about 2,100 lb higher, and after 1 day, about 3,400 lb higher. The data were less scattered than the data from tests with cartridges encased in 0.0014-in wrappers, but more scattered than the data from tests with cartridges encased in 0.003-in wrappers. The load was not maintained after the peak load capacity

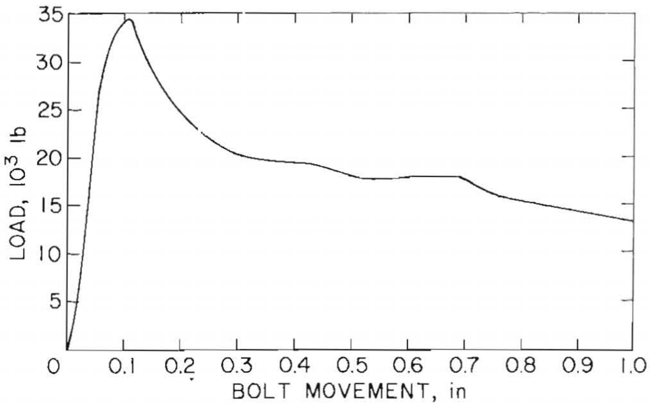

FIGURE 18. - Pull test result of typical cartridge-grouted roof-bolt system (0.0014-in polypropylene wrapper).

was reached, and the load-versus-movement curve was similar to that shown in figure 13*B*.

Grouted With Plastic Cements

Table 8 shows the results of pull tests on bolt systems grouted with two types of plastic cement. The cements were formed from resins and fillers, and from hardeners that were contained in the respective chambers of sealed, dual-chambered cartridges. The cartridge diameter was slightly less than the width of the simulated hole, and the length was 18 in. The chambers containing the resins and hardeners ran lengthwise so that when a bolt was inserted, an intimate mix of the resin and hardener resulted in the cement. The cements began hardening rapidly after insertion to provide early strength for the bolt system.

One cement was composed of polyester resin, and the other was composed of epoxy resin. The first (Fasloc[10]) is widely used commercially. All three Fasloc-cartridge-installed bolts broke, and no movement within the cement was noted. The second was an experimental cement made by Amicon. Mixed load capacities ranging from 20,325 to 39,025 lb resulted from the pull tests of Amicon-cartridge-installed bolts. Voids were noted in

[10]Reference to specific products does not imply endorsement by the Bureau of Mines.

TABLE 8. - Pull test results on 2-ft simulated roof bolts grouted with commercial resin cartridges

(Conditions: Concrete holes, 1-h cure time, 154-r/min rotation)

Test	Max load, lb	Movement site	Wrapper disposition[1]
		FASLOC	
80[2]...	37,200	No movement.	Dispersed.
81[2]...	37,800	...do.......	Intact, lower 18 in.
82[2]...	37,600	...do.......	Intact, lower 12 in.
		AMICON	
83....	29,925	Wrapper-hole	Dispersed.
84[3]...	20,325	Resin-hole..	Do.
85[2,3].	39,025	No movement.	Do.

[1]Upper hole is that portion nearest the bolt insertion end.
[2]Bolt broke.
[3]Extended mix time.

tests 83 and 84. The movment site occurred between the cartridge wrapper and hole wall in 83 and the resin and hole wall in test 84. The mix times for tests 83, 84, and 85 were 20, 80, and 60 s, respectively, and may have been the most important factor affecting load capacity.

As stated earlier, because the wrappers remained intact between the resin and hole wall, the tests with Fasloc cartridges led to the conclusion that, at least in 2-ft bolt systems, neither the cartridge wrapper nor the position of the wrapper after bolt insertion has a recognizable effect on bolt system load capacity. Extending this conclusion to bolt systems grouted with plaster-water capsule cartridges, results in the conclusion that the failure of these systems to reach load capacities up to the ultimate load of the steel itself must be due to the wax composing the capsules. It appears unnecessary to insure that wrappers are dispersed.

SUMMARY OF PULL TEST RESULTS

The average pull test load capacities and statistical significance of most test series are shown in table 6. Because the bolts broke, the results for the three categories of plaster-slurry-grouted bolt tests and the commercial Fasloc-cartridge-grouted bolt tests indicate the fracture load of the bolt steel rather than the grouted bolt system. The coefficient of variation (one standard deviation divided by mean multiplied by 100) for these tests is less than 5 pct. Bolt systems grouted with plaster-water capsule mix in 0.003-in polyethylene wrappers had load capacities roughly equivalent to bolt systems grouted with the same mix encased in 0.0014-in polypropylene and 0.0010-in polypropylene-saran wrappers. Greater variation among load capacities was evident with cartridge-grouted bolt systems, but among cartridge-grouted bolts, the least variation occurred with bolt systems grouted with cartridges encased with 0.003-in polyethylene wrappers. Load capacity equal to the capacity obtained with plaster-slurry-grouted bolt systems was achieved in cartridge-grouted bolts when the water-cement ratio was decreased to 0.288.

CREEP TESTS

CREEP TEST PROCEDURE

Slurry- and cartridge-grouted 2-ft simulated roof-bolt specimens were prepared identically to those used for pull testing, using the insertion machine shown in figure 8. In most instances, the specimens were cured for an hour before testing for creep. The creep tests were conducted in frames that were specially designed to accommodate six 2-ft specimens. As shown in figure 19, the 6-in projection of the bolt was attached to a deadweight load through a series of linkages and a 30-to-1 lever arm. The concrete simulated hole of the specimen was held stationary with respect to the frame. Calibration was maintained during a test by shortening the linkage between the bolt and the deadweight as the bolt moved out of the simulated hole.

The movement of a bolt was monitored continuously by a linear variable differential transformer (LVDT) that was attached between the bolt and the simulated hole. A computer was used to scan consecutively the analog signals from up to 10 specimens. The data signals from each specimen were collected and stored at a rate that was commensurate with the rate of creep. The computer provided instantaneous updates of elapsed time, total movement, minimum creep rate, and estimated movement in 10 yr.

Usually the creep rate, a measure of movement versus time, diminished with time. The estimated movement over a 10-yr span consisted of the total movement over the elapsed time of the test plus calculated movement at the minimum creep rate for the balance of the 10-yr period. Most tests were discontinued when changes in the minimum creep rate were judged sufficiently small. (As discussed later, this judgment proved more difficult than initially realized.) Some tests were discontinued shortly after the specimens were installed in the creep frames because movement was excessive, and the creep rate was not decreasing. Excessive movement was caused by undergrouting or loading above the apparent creep capacity of the bolt system. For comparison, the total movement at an arbitrary time, 1,000 h, was also computed. In some cases, generally depending on the load, 1,000 h was sufficient to establish the minimum creep rate.

TWO-FOOT SIMULATED ROOF BOLTS

Grouted With Plaster Slurry

All plaster-slurry-grouted specimens contained water at a water-cement ratio of 0.370. As shown in table 9, all tests except number 2 contained maximum grout. The bolts were loaded from 5,632 to 15,488 lb and, except for 2, were left under load for a minimum of 1,800 h. Because of undergrouting, the movement of the bolt in test 2 was excessive, and the test was discontinued after 718 h. A minimum creep rate could not be determined, and consequently, an estimated 10-yr movement could not be calculated.

FIGURE 19. - Creep test frame loaded with six 2-ft simulated roof-bolt specimens.

TABLE 9. - Creep test results on 2-ft simulated roof bolts grouted with plaster slurry

(Conditions: 0.370 water-cement ratio, concrete holes, 360-r/min rotation)

Test	Total grout, g	Load, lb	Total time, h	Movement in 1,000 h, in	Total movement, in	Minimum creep rate, 10^{-3} in/h	Est 10-yr movement, in
1....	332	5,632	1,819	0.0066	0.0070	0.0013	0.12
2[1]...	275	8,775	718	NAp	.082	ND	ND
3....	323	8,800	2,501	.0183	.0193	.0005	.06
4....	320	11,000	2,357	.0246	.0261	.0008	.09
5....	328	11,264	1,843	.0269	.0287	.0046	.42
6....	331	14,080	2,848	.0001	.0004	0	.00
7....	331	15,488	2,848	.0007	.0014	.0014	.12

NAp Not applicable. ND Not determined.
[1]Undergrouted; movement between grout and bolt.

The remaining bolts appeared to be uninfluenced by the load applied. The estimated 10-yr movements were all under 0.5 in. While a typical movement-versus-time curve for slurry-grouted bolt systems, shown in figure 20, gives the impression that the minimum creep rate has been established in about 1,000 h, the minimum creep rate is in fact continuously decreasing. For this reason, it is likely that the estimated movement for test 5, the bolt with the greatest movement, would have been lower had the test been continued several hundred hours longer. The average estimated 10-yr movement could have been as low as 0.1 in. The three bolts that showed low 1,000-h movement (tests 1, 6, and 7) were cured for 4 h rather than for 1 h.

Approximately 6 in of bolt was included in the measurement span of the LVDT.

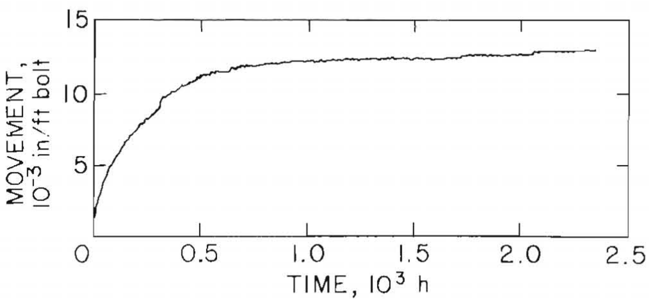

FIGURE 20. - Typical creep test curve for all systems specimens.

While the data do not differentiate between the extension of the bolt itself and the movement of the bolt from the simulated hole, the bolt extension over the loads employed was less than 0.001 in. Movement was not evident in the section analysis of the specimens except for that of test 2, which was incompletely grouted between most ribs because the plaster apparently was not fluid enough to flow between the ribs during insertion. Normally, as shown in figure 20, over 80 pct of movement occurred initially in the first 500 h.

It can be concluded that plaster-slurry-grouted roof bolt systems in lengths of 2 ft or greater can support loads of at least 15,500 lb with virtually immeasurable movement over 10 yr. The maximum possible sustained load was not determined because of loading limitations of the equipment.

Grouted With Plaster-Water Capsule Mix Encased In 0.003-In Polyethylene Wrappers

Cartridge-grouted specimens were made using concrete simulated holes and the same procedure that was used for making pull test specimens. The cartridges contained the water capsule-plaster mix in a 0.500 ratio to give a water-cement ratio of 0.319. Table 10 shows the results of creep tests at various loads.

TABLE 10. - Creep test results on 2-ft simulated roof bolts grouted with plaster-water capsule mix encased in 0.003-in polyethylene wrappers

(Conditions: 0.319 water-cement ratio, 0.500 capsule-gypsum ratio, concrete holes)

Test	Total grout, g	Load, lb	Total time, h	Movement in 1,000 h, in	Total movement, in	Minimum creep rate, 10^{-3} in/h	Est 10-yr movement, in
8....	304	4,378	15,063	0.1677	0.2279	0.0011	0.31
9....	300	4,558	4,623	.0362	.1320	.0056	.60
10...	266	5,485	1,221	.154	.1622	.4440	38.54
11...	313	5,500	2,501	.0350	.0378	.0024	.24
12...	291	5,632	4,160	1.1419	1.4105	.0267	3.64
13...	281	5,697	1,218	.1685	.1862	.0790	7.01
14[1]..	300	6,836	2,123	.9772	1.5497	.2885	26.23
15...	298	7,040	1,843	.0816	.0897	.0097	.92
16...	279	7,661	1,444	1.6201	2.5392	.2860	27.20
17[2]..	311	8,448	5,276	.0064	.0099	.0027	.23
18[3]..	304	8,775	1,058	1.7656	1.7996	.3474	31.89
19...	304	9,115	11,524	.8855	1.6340	.0180	3.00
20[2]..	311	9,856	10,330	.0165	.0425	.0059	.50
21...	287	9,872	1,221	1.9817	2.0746	.4297	39.21
22[1]..	310	10,255	74	NAp	1.3347	ND	ND
23...	294	10,944	1,444	1.7408	1.9650	.4750	42.92
24...	307	11,264	1,085	1.1616	1.1623	ND	ND
25...	304	11,264	259	NAp	.1585	ND	ND
26...	299	11,264	1,127	1.3352	1.3356	ND	ND
27...	315	12,672	1,085	1.0040	1.0142	ND	ND
28...	303	12,672	259	NAp	.4216	ND	ND
29...	304	12,672	1,127	.7792	.7799	ND	ND
30...	307	14,080	1,127	.4282	.4299	ND	ND

NAp Not applicable. ND Not determined.
[1]Grout leaked through crack in concrete.
[2]21-s insertion.
[3]Cured for 10 days and pulled to 34,700 lb prior to creep testing.

More variation exists in the results of the cartridge-grouted creep tests than in the slurry-grouted creep tests. Like the slurry-grouted specimens, the ultimate creep load of the cartridge-grouted specimens was influenced substantially by undergrouting. Although specimens with 275 g of grout were capable of withstanding an above standard load (17,700 lb) in pull testing, the ultimate creep load was adversely affected if a specimen contained less than about 300 g. The adverse effect is exemplified by tests 10, 12-14, 16, 18-19, and 21. The specimen in test 23 was also undergrouted, but in addition, it appears that it was overloaded. It sustained more movement than any other specimen. The specimen in test 14, while appearing adequately grouted, lost grout through a crack in the concrete and was weak.

The minimum creep rates upon which the estimated 10-yr movements were based continually decreased, and as a consequence, the estimated 10-yr movements for identical bolts loaded at identical loads differed significantly, depending upon the duration of the creep test. Table 10 contains two examples that serve to illustrate the effect of test duration. Specimens in tests 12 and 13 were undergrouted and contained 291 and 281 g, respectively. Both were loaded at about 5,650 lb. In 1,000 h, 12 had experienced 1.1419 in of movement while 13 had experienced 0.1685 in of movement. Intuitively, it could be expected that because its 1,000-h movement was greater, movement of specimen 12 at any other time interval would be greater. However, the estimates for 10-yr movement are quite the opposite because 12 was tested over three times longer than 13, and hence, its minimum creep rate was almost half that of 13.

Because in several cases the creep rate continued to decline and a steady state was never reached, the question arose as to when a test should be terminated. Consequently, longer term tests were computer simulated by projecting the decline in the minimum creep rate by a straight-line method. The estimated 10-yr movements were recomputed for five specimens that showed excessive creep. The minimum creep rates were determined at 17,520 h (2 yr) by projecting the plot of each specimen's time-versus-movement curve forward from the last recorded data point. In all cases, the minimum creep rates were reduced to extremely low levels, the highest being 5×10^{-7} in/h. These creep rates are greater than the actual rate, since in reality, minimum creep rates declined faster than predicted by the straight-line method. As shown in table 11, the 10-yr estimated movements of two specimens (tests 18 and 21) dropped dramatically when based upon the 2-yr projected minimum creep rate. The new 10-yr estimated movements of two other specimens (tests 14 and 23) changed little, and the estimated movement of the specimen in test 10 was lowered by about two-thirds. The projections emphasize the value of long-term creep tests.

While more than 95 pct of the movement appears to occur in less than 2 yr, estimated movements based upon minimum creep rates determined from data collected from tests of less than 2,000 h may lead to erroneous and unwarranted results, especially with specimens that are undergrouted.

This conclusion can probably only be applied to specimens that have been loaded at less than 10,000 lb. Numerous specimens were loaded at various levels above 10,000 lb, and excessive movement was noted in each within 1,000 h or less. Table 10 shows nine tests, 22 through 30, that exhibit such behavior. Movement was so fast that proper load adjustments could not be maintained on the creep frame apparatus. Moreover, since most of these specimens were adequately grouted, it appears that a threshold creep strength, at least for 2-ft bolts, exists at a loading of about 10,000 lb. Above this load, rapid and excessive movement can be expected.

Each specimen also was sectioned. The section observations were the same as those for most pull test specimens in which 0.003-in polyethylene-wrapper-encased cartridges were used. The shear interface in the upper specimen was located between the bolt and grout. In the lower one-half to two-thirds of the specimen, the interface was located between the grout and the intact wrapper. In addition, each specimen contained a section of shiny, waxlike material. The failure mechanism of the pull and creep specimens also appeared similar. Grout adhered to the upper hole wall and formed

TABLE 11. - Changes to the estimated 10-yr movement based upon computed 2-yr minimum creep rates

Test	Minimum creep rate, 10^{-3} in/h	Original est 10-yr movement, in	Computed minimum creep rate after 2 yr, 10^{-3} in/h	Est 10-yr movement based on 2-yr minimum creep rate, in
10...	0.444	38.54	0.00002	10.50
14...	.289	26.23	.00030	23.41
18...	.347	31.89	.00008	2.49
21...	.430	39.21	.00001	2.96
23...	.475	42.92	.00050	41.20

a collar around the bolt, and the grout in the lower hole moved with the bolt against the collar.

Grouted Under Miscellaneous Conditions

Table 12 lists the results of several tests on specimens that were grouted with cartridges containing different water-cement ratios, wrappers, or cements. The specimen for test 31 was installed with a cartridge containing plaster-water capsule mix in a 0.003-in polyethylene wrapper but at a 0.288 water-cement ratio. The estimated 10-yr movement was greater by almost an order of magnitude than the estimated movement of specimen 11, the best specimen from table 10 that was loaded similarly but grouted at a water-cement ratio of 0.319. The wrapper was intact in the lower 18 in of hole, and the bolt was adequately grouted. There was no evidence that indicated the cause of the excessive movement.

The specimen for test 32 was grouted with a plaster-water capsule cartridge with a 0.0014-in polypropylene wrapper. The projected 10-yr creep rate was 0.06 in even though the bolt was undergrouted. The wrapper was left intact for the lower 19 in of simulated hole, and movement in this section was between the simulated hole and wrapper.

Specimens for tests 33 and 34 were 4 ft long, and each contained two 23-in cartridges. The simulated holes were initially cast at 5/8-in diam and bored to the 1-1/32-in diam. The bolts were inserted with commercial equipment. The cartridge wrapper in test 33 was 0.0014-in polypropylene, while the wrapper in test 34 was 0.003-in polyethylene. The cure time was 41 days, and both specimens were loaded at 14,080 lb. Specimen 33 had a total 10-yr estimated movement of 1.05 in, but 34 had a total movement of 9.67 in. The minimum creep rate for 33 was established in about 1,000 h, but the minimum creep rate for 34 did not occur until 3,500 h had elapsed. The result of test 33 suggests that superior creep resistance is obtainable with bolt systems containing cartridges enclosed in 0.0014-in polypropylene wrappers. However, multiple tests were not run, and statistically significant emphasis cannot be added to insignificant results.

Additional tests (35 through 37 in table 12) were done on bolt systems that were grouted with Amicon epoxy and commercially available Fasloc polyester cartridges. The bolt systems were loaded to 14,080 lb, and negligible movement was sustained.

TABLE 12. - Creep test results on 2- and 4-ft simulated roof bolts grouted under miscellaneous conditions

Test	Total grout, g	Load, lb	Total time, h	Movement in 1,000 h, in	Total movement, in	Minimum creep rate, 10^{-3} in/h	Est 10-yr movement, in
31[1]..	313	5,500	2,501	0.0509	0.0567	0.0226	1.98
32[2]..	284	5,500	2,501	.0297	.0302	.0003	.06
33[2,3]	Unk	14,080	2,479	.0169	.0319	.0120	1.05
34[3]..	Unk	14,080	8,009	.1692	.3906	.1165	9.67
35[4]..	NAp	14,080	5,482	.0006	.0323	.0008	.10
36[4]..	NAp	10,560	5,482	.0007	.0020	.0002	.02
37[5]..	NAp	14,080	2,455	.0166	.0061	.0013	.12

Unk Unknown. NAp Not applicable.
[1]0.288 water-cement ratio.
[2]0.0014-in wrapper.
[3]4-ft bolt.
[4]Amicon resin.
[5]Fasloc resin.

FOUR-FOOT INSTRUMENTED, SIMULATED ROOF BOLTS GROUTED WITH PLASTER-WATER CAPSULE MIX ENCASED IN 0.003-IN POLYETHYLENE WRAPPERS

Two narrow grooves were milled opposite one another along the length of a 4-ft bolt, and 12 strain gauges were embedded in the grooves. The bolt was installed in a 4-ft simulated hole with two cartridges containing plaster with water capsules at a 0.500 ratio. The bolt system was loaded at 4,500, 9,000, and 13,500 lb in three separate loadings, and the load at each strain gauge was monitored. Prior to each new loading, the load was relaxed.

Figure 21 shows that the total bolt system movement was small and that the minimum creep rate was reached early (at about 600 h) during the first loading at 4,500 lb. The jump in the movement for the 9,000-lb loading was most likely due to an experimental error.

At all loadings, most of the load was borne by the upper half of the bolt. Figure 22 shows the load distribution at the three loadings. No significant change with time was noted in the load distribution after 24 h. These data suggest that 4-ft bolt systems are better able to withstand higher loads than 2-ft bolts without creep movement.

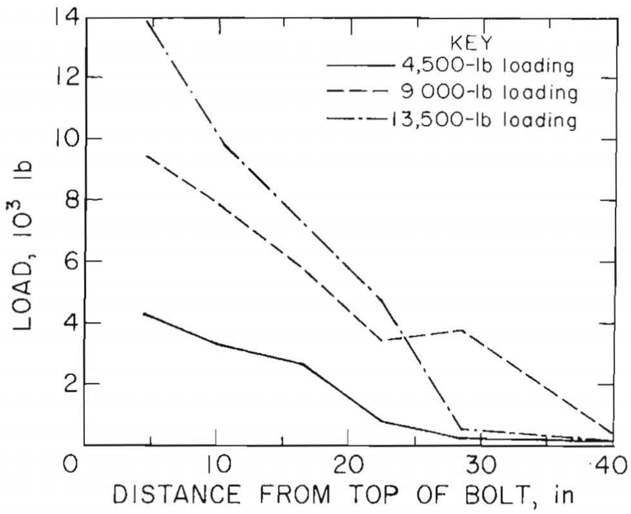

FIGURE 21. - Movement at 4,500-, 9,000-, and 13,500-lb loadings of a 4-ft instrumented, simulated roof-bolt system.

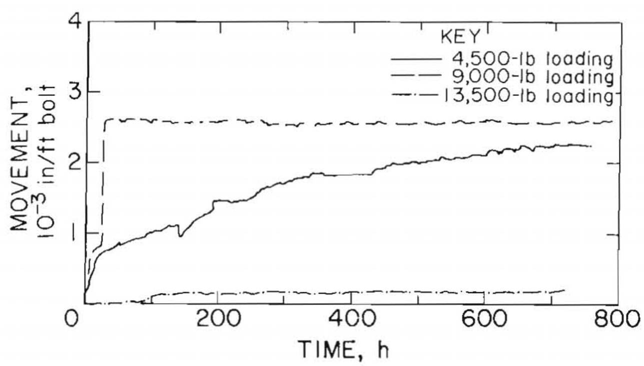

FIGURE 22. - Load distribution along the 4-ft instrumented roof-bolt system of figure 21 at 4,500-, 9,000-, and 13,500-lb loadings.

SUMMARY AND CONCLUSIONS

Unless noted, the following conclusions apply to 2-ft roof bolts grouted within concrete simulated holes. The conclusions are highlighted in table 13.

1. Gypsum plasters of the type that are proposed for roof bolting have less than 0.5 pct impurity and are uniform from lot to lot and supplier to supplier.

2. With cure times less than 10 min, the load capacity of slurry-grouted roof bolt systems at a water-cement ratio of 0.370 equals the ultimate capacity of bolt steel, which is about 37,000 lb. Grout movement within the hole is not observable.

3. At a greater than 0.370 water-cement ratio, the load capacity of slurry-grouted roof bolt systems becomes dependent upon curing duration. Movement occurs at curing durations less than 23 min. The load capacity at a cure time of 10 min is about 31,000 lb, still well above the 17,700-lb requirement.

4. At water-cement ratios less than 0.370, slurry is more viscous than at higher ratios and may be difficult to place in a bolt hole without causing undergrouting and excessive voids.

TABLE 13. - Highlights of conclusions for normally grouted 2-ft roof bolts

Anchoring system	Water-cement ratio	Ultimate load capacity, lb: 10-min cure time	Ultimate load capacity, lb: 1-h cure time	Creep capacity, lb	Remarks
Slurry	0.370	>37,000	>37,000	>15,500	Slurry is highly viscous at water-cement ratios <0.370.
	.400	31,000	ND	ND	Load capacity dependent on cure time.
Cartridge:					
0.003-in polyethylene wrapper.	.319	30,300	27,900	<10,000	Wrappers remain largely intact between grout and hole wall.
	.288	ND	37,300	~10,000	Bolt insertion is difficult.
0.0014-in polypropylene wrapper.	.319	ND	27,400	ND	Wrappers remain largely intact between grout and hole wall.
0.0010-in polypropylene and saran wrapper.	.319	ND	29,600	ND	Do.
Fasloc, resin-grouted	NAp	ND	[1]>37,500	>14,000	Commercially in use.

ND Not determined. NAp Not applicable. [1]1-day cure time.

5. Undergrouting usually results in a loss of load capacity depending upon the degree of undergrouting and whether or not voids are scattered or concentrated. The degree of undergrouting that can be safely tolerated was not determined for slurry-grouted bolt systems.

6. When movement occurs in slurry-grouted bolt systems, the failure interface lies between the bolt and grout.

7. Bolt system load capacity may be reduced substantially in hole mediums that are weaker than concrete. Failure may occur in the mediums rather than the grout or bolt.

8. Dampened holes do not affect pull test load capacity.

9. Slurry-grouted roof bolt systems can sustain constant loads of at least 15,500 lb for long terms without incurring predicted 10-yr movement of more than 1/2 in. The ability of slurry-grouted bolt systems to withstand heavier, long-term loads was not determined.

10. With fully grouted slurry-grouted bolt systems, a coefficient of variation of less than 5 pct can be obtained from pull tests.

11. With cure times of 10 min, the load capacity of polyethylene wrapper cartridge-grouted roof bolt systems at a water-cement ratio of 0.319 is about 30,300 lb; at 1 h, about 27,900 lb; and at 7 days, about 31,500 lb.

12. At a cure time of 1 h, the load capacity of polyethylene wrapper cartridge-grouted roof bolt systems at a water-cement ratio of 0.288 is about 37,300 lb. Insertion is more difficult.

13. Cartridge wrappers remain intact between the grout and hole wall in the lower three-quarters of hole.

14. Wrappers made with polypropylene and combinations of polypropylene and saran also remain intact between the grout and hole wall. The load capacities of bolt systems installed with cartridges encased in these wrappers are roughly

similar to the load capacities of bolt systems installed with cartridges encased in polyethylene.

15. The grout from cartridge-installed specimens shows two forms: (1) a form in which the gypsum crystallites appear similar to cast gypsum except shorter and more cylindrical and (2) a shiny, waxlike form in which the gypsum crystallites are obscured. The waxlike form appears to result when the wax capsule remnants are smeared and dispersed by pressure during testing.

16. When movement occurs within a hole between the bolt and anchoring medium in cartridge-grouted bolt systems, the failure interface lies between the bolt and grout in approximately the upper one-quarter of hole (nearest the bolt head) in which the wrapper has dispersed and between the grout and wrapper in approximately the lower three-quarters of hole in which the wrapper remains intact. During pull testing, the upper grout acts as a collarlike retainer for the lower grout, which is compressed against it.

17. Bolt systems that are grouted with commercial cartridges made of polyester resin and also encased in plastic wrappers have load capacities equal to slurry-grouted bolt systems without wrappers, suggesting that wrappers are not an independent variable that affects load capacity. With the wrapper eliminated as a factor, the wax, which accounts for approximately 20 vol pct of the grout, is the most likely cause of weakness in cartridge-grouted bolt systems. As far as load capacity is concerned, it appears unnecessary to insure the complete break-up and dispersion of wrappers.

18. Cartridge-grouted bolt systems that are loaded but sustain no movement can be relaxed and reloaded without suffering a loss of load capacity.

19. Undergrouting occurs more readily with cartridge-grouted bolt systems than with slurry-grouted bolt systems because high pressure during insertion forces excess grout out of the hole or into cracks in the hole wall. Undergrouting by as much as 55 to 70 g from a 330-g cartridge can be tolerated without undue loss of load capacity. As with slurry-grouted bolt systems, the degree and concentration of voids is a factor in determining loss of load capacity.

20. Consistency is harder to obtain in pull tests with cartridge-grouted bolt systems than with slurry-grouted bolt systems.

21. Cartridge-grouted roof-bolt systems can sustain constant loads up to about 10,000 lb for long terms without excessive creep movement. Above 10,000 lb, creep is excessive. Again, the wax is the most likely cause of the reduction in load capacity in comparison with slurry-grouted bolt systems.

22. Although undergrouting by 55 to 70 g from a 330-g cartridge does not cause undue loss of load capacity, undergrouting by more than 30 g can result in excessive creep movement.

23. The mechanism by which failure occurs during creep testing of cartridge-grouted bolt systems is the same as that that occurs during pull testing.

24. Undergrouted cartridge-installed bolt systems and heavily loaded bolt systems may require testing for up to 2 yr before accurate predictions of creep movement can be made. Because minimum creep rates decrease at a decreasing rate and long-term projections are functions of the minimum creep rate, the projections are lower with longer test times.

25. Additional long-term creep tests on undergrouted cartridge-installed bolt systems and heavily loaded bolt systems are needed to provide reliable engineering data and to determine the reasons for diminishing creep rates.

26. In 4-ft cartridge-grouted bolt systems, most of the load is borne by the upper 2 ft of bolt system, and little shift in the load distribution occurs with time. However, cartridge-grouted 4-ft bolt systems may be able to resist creep better than 2-ft bolt systems. Additional tests are needed to determine whether bolt length is a significant variable that influences creep.

27. Commercially available Fasloc-resin-grouted bolt systems are capable of resisting creep at constant loads of at least 14,000 lb.

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